National Library
of Canada

Acquisitions and
Bibliographic Services Branch

395 Wellington Street
Ottawa, Ontario
K1A 0N4

Bibliothèque nationale
du Canada

Direction des acquisitions et
des services bibliographiques

395, rue Wellington
Ottawa (Ontario)
K1A 0N4

Your file Votre référence

Our file Notre référence

NOTICE

The quality of this microform is heavily dependent upon the quality of the original thesis submitted for microfilming. Every effort has been made to ensure the highest quality of reproduction possible.

If pages are missing, contact the university which granted the degree.

Some pages may have indistinct print especially if the original pages were typed with a poor typewriter ribbon or if the university sent us an inferior photocopy.

Reproduction in full or in part of this microform is governed by the Canadian Copyright Act, R.S.C. 1970, c. C-30, and subsequent amendments.

AVIS

La qualité de cette microforme dépend grandement de la qualité de la thèse soumise au microfilmage. Nous avons tout fait pour assurer une qualité supérieure de reproduction.

S'il manque des pages, veuillez communiquer avec l'université qui a conféré le grade.

La qualité d'impression de certaines pages peut laisser à désirer, surtout si les pages originales ont été dactylographiées à l'aide d'un ruban usé ou si l'université nous a fait parvenir une photocopie de qualité inférieure.

La reproduction, même partielle, de cette microforme est soumise à la Loi canadienne sur le droit d'auteur, SRC 1970, c. C-30, et ses amendements subséquents.

Canada

University of Alberta

AN EFFICIENT ANALYTICAL APPROACH FOR GENERATING DIGITAL ELEVATION MODELS

BY

DANIEL HEMENWAY ©

A Thesis
Submitted to the Faculty of Graduate Studies and Research
in partial fulfillment of the requirements
for the degree of
MASTER OF SCIENCE

DEPARTMENT OF GEOGRAPHY

EDMONTON, ALBERTA
FALL 1995

National Library
of Canada

Acquisitions and
Bibliographic Services Branch

395 Wellington Street
Ottawa, Ontario
K1A 0N4

Bibliothèque nationale
du Canada

Direction des acquisitions et
des services bibliographiques

395, rue Wellington
Ottawa (Ontario)
K1A 0N4

Your file Votre référence

Our file Notre référence

THE AUTHOR HAS GRANTED AN IRREVOCABLE NON-EXCLUSIVE LICENCE ALLOWING THE NATIONAL LIBRARY OF CANADA TO REPRODUCE, LOAN, DISTRIBUTE OR SELL COPIES OF HIS/HER THESIS BY ANY MEANS AND IN ANY FORM OR FORMAT, MAKING THIS THESIS AVAILABLE TO INTERESTED PERSONS.

L'AUTEUR A ACCORDE UNE LICENCE IRREVOCABLE ET NON EXCLUSIVE PERMETTANT A LA BIBLIOTHEQUE NATIONALE DU CANADA DE REPRODUIRE, PRETER, DISTRIBUER OU VENDRE DES COPIES DE SA THESE DE QUELQUE MANIERE ET SOUS QUELQUE FORME QUE CE SOIT POUR METTRE DES EXEMPLAIRES DE CETTE THESE A LA DISPOSITION DES PERSONNE INTERESSEES.

THE AUTHOR RETAINS OWNERSHIP OF THE COPYRIGHT IN HIS/HER THESIS. NEITHER THE THESIS NOR SUBSTANTIAL EXTRACTS FROM IT MAY BE PRINTED OR OTHERWISE REPRODUCED WITHOUT HIS/HER PERMISSION.

L'AUTEUR CONSERVE LA PROPRIETE DU DROIT D'AUTEUR QUI PROTEGE SA THESE. NI LA THESE NI DES EXTRAITS SUBSTANTIELS DE CELLE-CI NE DOIVENT ETRE IMPRIMES OU AUTREMENT REPRODUITS SANS SON AUTORISATION.

ISBN 0-612-06481-6

Canada

University of Alberta

Library Release Form

NAME OF AUTHOR: **Daniel David Hemenway**

TITLE OF THESIS: **An Efficient Analytical Approach for Generating Digital Elevation Models**

DEGREE: **Master of Science**

YEAR THIS DEGREE GRANTED: **1995**

Permission is hereby granted to the University of Alberta Library to reproduce single copies of this thesis and to lend or sell such copies for private, scholarly, or scientific research purposes only.

The author reserves all other publication and other rights in association with the copyright in the thesis, and except as hereinbefore provided, neither the thesis nor any substantial portion thereof may be printed or otherwise reproduced in any material form whatever without the author's prior written permission.

12615- 42 Ave.
Edmonton, Alberta, Canada
T6J 0X3

August 1, 1995

University of Alberta

Faculty of Graduate Studies and Research

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled AN EFFICIENT ANALYTICAL APPROACH FOR GENERATING DIGITAL ELEVATION MODELS submitted by DANIEL DAVID HEMENWAY in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE.

J. Ronald Eyton

Dr. J. Ronald Eyton

Ian Campbell

Dr. Ian Campbell

P A Crown

Dr. Peter Crown

July 27, 1995

Dedicated to
Toga, Trinket, Mist,
the pups
and most importantly
Allana
-for always being there-

Abstract

Digital elevation models (DEMs) have become vital data for nearly every profession which deals directly or indirectly with studying, planning, or developing land. Generating DEMs necessary for many of these applications can be an expensive and time consuming endeavor. Developing a computerized image processing approach to perform the task of digitizing map contours provided a means for even inexperienced users to acquire digital topographic information in an accurate and affordable manner. Analytical surfacing methodologies based on multiquadric equations produce DEMs that are exact fitting and free of artifact irregularities associated with currently popular numerical approaches. Multiquadric equations generate global surfacing solutions involving all initial points. Limitations in computer memory and processing power prevent the use of multiquadric equations for large topographic data sets. An adaptive global tiling approach was developed which overcomes these impediments by strategically partitioning data points into manageable subsets, allowing implementation of multiquadric interpolation techniques on any computer system.

Acknowledgements

I would like to acknowledge and thank my supervisor, Dr. Ron Eyton, for his many years of support while this project evolved. I would also like to thank Dr. Ian Campbell and Dr. Peter Crown for their input and contributions to the final thesis. Stu Cruikshank, Kent Holden, Darren Sjogren, Craig Coburn and many others over the years must be thanked for patiently testing and re-testing the different pieces of software developed in this project. I would like to acknowledge and thank the entire Department of Geography for the many years of employment and support and especially Joan MacLeod for keeping the red tape to a minimum. Finally, I would like to thank Allana Hemenway for the years of patient support and direction. Her presence provided the focus, stability, and environment for making this dream come true.

Table of Contents

Chapter 1 Introduction 1

The Need for an Efficient Methodology for Generating DEMs 2
Research Objectives 3

Chapter 2 A Brief Review of Surfacing Methodology 4

Data Sources 4
Acquisition of Secondary Data 5
Surface Generation 6

Chapter 3 Methodology Overview 8

Test Data 8
Image Processing for Digital Data Capture 8
Data Management for Small Computers 10
An Analytical Tiling Approach to Surfacing 11

Chapter 4 Image Processing for Digital Data Capture 13

Scanning Topographic Maps 13
Image Processing 15
Elevation Encoding 15
Image Data Reduction 18
Extracting Elevation Information from a Raster Image 21

Chapter 5 Data Management for Small Computers 22

Range Searching 22
Two Dimensional Binary Search Trees 23

Chapter 6 An Analytical Tiling Approach to Surfacing 26

Multiquadric Equations 27
Tiling 29

Tile Boundary Effects 30
Adaptive Tiling 30
Directional Point Selection 31

Post-Processing 31
Qsurf 34

Chapter 7 Comparison with the Alberta 1:20,000 DEM 39

Edge Contours 39
Lambertian Light Model 41
Slope Magnitude 41
Across Slope Curvature 41
Down Slope Curvature 45
Statistical and Numerical Comparisons 47

Chapter 8 Summary 51

References 53

List of Tables

Table 7.1 Residual Surface Cumulative Frequency Distribution **50**

List of Figures

Figure 3.1 Three dimensional view of the topography in map sheet 83C/01NW. View azimuth is 210° at an elevation of 28°. Solar illumination is from an azimuth of 140° at an elevation of 30°. Vertical exaggeration is 1X. 9

Figure 4.1 Sample scans at: a. coarse; b. medium; c. fine resolutions. 14

Figure 4.2 Rotation of scanned map segments for rectangular alignment of UTM registration marks 16

Figure 4.3 Contour lines are isolated by erasing connecting pixels along the contour borders. 17

Figure 4.4 A contour mask is created by thresholding a copy of the scanned image. The mask is pasted over the final encoded image to thin the contours to their centers. 20

Figure 5.1 Sample two dimensional binary search tree with 11 nodes containing XYZ coordinate information. 24

Figure 6.1 Example summary for evaluating a multiquadric solution.
Source: Eyton, 1974 28

Figure 6.2 Point density variations over the area of a uniform tile may cause surface discontinuities with adjacent tiles. 32

Figure 6.3 For adaptive directional tiling, similar numbers of points are selected from eight sectors radiating around the tile center. Sector sizes adapt to local density variations in data point distributions. **33**

Figure 6.4 Even with adaptive directional tiling, specific patterns in data point distributions can cause surface discontinuities at tile boundaries. **35**

Figure 6.5 Performance chart indicating the relationship between total surfacing time and average number of points selected from each sector of a tile partition. **37**

Figure 7.1 Edge contour images. Base reference elevation is 1300m. Contour interval is 50m. **40**

Figure 7.2 Relative radiance images using a Lambertian Light model. Solar illumination is from 300° at an elevation of 30°. **42**

Figure 7.3 Slope magnitude images. Maximum magnitudes were clipped at 48° of slope to enhance low-magnitude slope details. **43**

Figure 7.4 Across slope curvature scaled between -80° and 80° of change in slope per 100m. **44**

Figure 7.5 Down slope curvature scaled between -80° and 80° of change in slope per 100m. **46**

Figure 7.6 Residual difference image produced by subtracting the Qsurf DEM from the SCOP DEM. Differences are scaled between -10m (black) and +10m (white). **48**

Chapter 1
Introduction

For centuries topographic and elevation information was vaguely represented in two dimensions by lines, symbols, and shades on map-like products. As technology evolved and methods of measuring changes in elevation became more precise, cartographic representation of elevations evolved from these loosely defined artistic impressions to accurately located contour lines connecting locations of equal topographic value. Elevation data presented in the format of accurate map contours permitted useful numerical information to be extracted through simple, though tedious calculations. Today, the high degree of accuracy obtainable for measuring, storing, and displaying the surface of the earth has increased demand for new methods of extracting information from positional measurements. Nearly every profession which deals directly or indirectly with studying, locating, or developing land now requires accurate calculations based on detailed topographic information. The advent of the computer has provided both the ability and the drive to extract large quantities of meaningful information from terrain data at high precision. As the processing power of computers has increased, combined with a steady decrease in computer costs, more applications than ever require topographic data collected and stored in digital format.

Digital representation of topographic information has evolved into two dominant formats over the past twenty years. The two formats are closely tied to the traditional raster and vector methods of displaying or representing items of information at discrete locations. The two methods of representing topographic information are the Digital Elevation Model (DEM) and the Triangulated Irregular Network (TIN) model.

The DEM format consists of elevation values stored in a matrix or raster arrangement where exact spatial locations are implied by row and column location. A value stored at a given matrix location is assumed to represent the characteristics of the entire area covered by the grid cell. Spatial coverage of a region by a DEM is complete since all grid cells in a matrix must exist for the matrix structure to be valid. A cell in the matrix may have an undefined value which does not reflect characteristics of the true land surface, however, the location of the cell and the surface area

represented by the cell are "guaranteed" by the rigid raster structure of the DEM.

The TIN format for storing topographic information follows the traditional vector approach. Elevation values stored in a TIN format are described by a complete set of three dimensional coordinates. The exact location of points in a TIN format dictates that there is no point-to-area generalization of the type inherent in the DEM format. Consequently, non-represented locations in the TIN format are not spatially identifiable without interpolation of the data.

The "guaranteed" coverage of the DEM format, combined with its simple data structure and modest storage requirements have increased the popularity of the DEM format and it is commonly used as a method for modelling and archiving the topography of the earth. A comprehensive evaluation of the accuracy and effectiveness of the DEM format as compared to the TIN format conducted by Kumler (1994) concluded that in all cases investigated, the DEM format was equal to or superior to the TIN format in storing, processing, and presenting topographic information.

The Need for an Efficient Methodology for Generating DEMs

Traditional DEM production has required the use of specialized and sophisticated combinations of hardware and software. These requirements demand large investments of capital resources and technical skill to collect topographic data and process the information into a useful product. Applications of topographic information in many disciplines has increased the need for DEMs to be accessible to individuals with limited equipment, capital, and training resources. Many small companies and individuals (e.g. geomorphologists involved in fieldwork) who would benefit from the use of DEMs in their work may not have the resources necessary to purchase or develop specialized DEMs generated by traditional methods. The need to produce accurate and effective DEMs in a timely and cost efficient manner can be expected to increase as the use and accessibility of Global Positioning System units rises over the next decade.

Research Objectives

The objectives of this research are:

1. To develop an accurate, effective, and affordable method of acquiring discretely located elevation data of sufficient quality and quantity as to be useful in generating a digital elevation model.

2. To develop a product by which irregularly distributed data values may be interpolated to produce an accurate representation of the surface topography limited only by the initial data capture.

The first objective contains several explicitly stated conditions that qualify the acceptability of any data acquisition method developed. The conditions that a method must be accurate, effective, and affordable dictate that the method must be spatially precise, simple to use without extensive training, and must utilize multi-purpose hardware or software to reduce allocation of resources to specialized tasks. A digitizing table is considered a specialized and single purpose piece of hardware which would not be available to many people and consequently would not be acceptable to the methodology restrictions given here. The second objective contains the restriction that the developed product generates an interpolated surface that exactly reproduces initial data values and reasonably represents the surface at all other locations. The program should be simple to use and should be executable in as many computing environments as possible.

Chapter 2
A Brief Review of Surfacing Methodology

Modelling continuous surfaces typically involves two distinct phases of operation. The initial phase involves sampling, correcting, and storing the discrete spatial values which represent the surface to be modelled. The second phase deals with organizing and interpreting sample data in order to calculate realistic values for unknown locations within the surface domain. The second phase also deals with the file format for storing and retrieving a generated surface model. The development of highly precise ortho-photo plotters, stereo-parallax satellite imagery, and laser profilers capable of sampling complete surface models directly has clouded the distinction between these two phases of operation; however, for general surfacing applications the two phases remain distinct from each other.

Data Sources

Sources of sample data representing geographic surfaces may be labelled as either primary or secondary. Primary sources provide the highest level of accuracy in measured topographic information. Common forms of primary data sources include ground surveys, aerial photographic stereo-pairs and ortho-photos, stereo-parallax satellite imagery, airborne laser profilers, and global positioning system measurements. Primary data sources provide topographic information by directly measuring a surface using physical sensing or photogrammetric techniques. The measurement process and precision requirements of primary data sources requires specialized equipment and training to collect and compile the data into useable form. The costs involved with acquiring data from primary sources prohibits the use of this type of data for many small scale and low budget applications.

Secondary topographic data sources are provided in a pre-processed format and yield generalized information about the characteristics of a surface. The most common and accessible source of secondary terrain information is the topographic map. Elevation information on a topographic map has been generalized into discrete categories delineated by contour lines. Elevation information within each category can only be estimated by

proximity to the bounding contours. With sufficiently small contour intervals the terrain information encoded in a topographic map may approach the accuracy of data provided from primary data sources. The cost of purchasing topographic maps is very small and maps at various scales are available for much of the earth's surface. Topographic data collected from secondary sources such as contour maps are commonly used for small scale terrain modelling applications.

Acquisition of Secondary Data

Converting analogue information from topographic maps into useable digital data typically requires the use of specialized hardware and the skill of a trained operator to digitize the elevation contours. Digitizing maps may occur in several different ways, however the underlying procedure of logging values at locations identified by a sensing device is a common characteristic. Differences in digitizing methods are generally attributed to the pattern and manner in which contours are selected for processing. *Line following* digitizing is the most common method and requires the use of a standard digitizing table. In line following digitizing, contours are traced by the operator using a location sensitive cursor or pen. Data values are recorded at regular intervals or at operator specified locations. Accuracy with line following digitizing is largely determined by the skill and steady coordination of the operator.

Contour crossing digitizing is an alternative to the line following method. The contour crossing pattern of digitizing requires moving a cursor in parallel scan lines across the face of a map sheet and recording a point whenever a contour line is encountered. While contour crossing digitizing can be performed on a standard digitizing table, this pattern of digitizing is usually performed on a specialized motor driven table where the spacing of parallel scan lines may be precisely set. Attempts have been made to automate both line following and contour crossing methods of digitizing through the use of sophisticated optical sensors and control programs. The resulting automated digitizing apparatus still requires operator intervention to differentiate ambiguous situations and to identify non-topographic symbology on the maps. A third method of converting map information to digital form is a process called *scan conversion*. With scan conversion, a map

is scanned as a raster image. Pattern recognition programs then try to identify and isolate the text, symbology, and contour information that is embedded in the image.

Surface Generation

The choice of methodologies available for generating topographic surfaces depends upon the type of elevation model in which the surface will be stored. When a triangulated irregular network model is used, data points are processed to determine an optimal triangular network from within the data. No further interpolation or addition of data points takes place. The two most often used methods for generating TIN models are the Delauney Triangulation and the Radial Sweep methods (Stefanovic, 1988). Both methods require intensive processing of the data points to construct networks of optimal triangles. When the digital elevation model is used to store a surface the number of surfacing methods available increases dramatically. For all DEM methods of generating surfaces, initial data points are interpreted to predict new values on a regular grid. The predicted grid values are then stored in the model and the initial irregularly distributed data points are discarded.

Techniques used to create modelling functions for DEMs depend in part upon the pattern followed in digitizing the map. When the contour crossing method of digitizing is used, modelling functions may be based on profiles fit through the data points along each scan line. When interpolation of scan lines occurs, two dimensional mathematical functions of linear, polynomial (splines) (Davis, 1973), and multiquadric (Eyton, 1987) profiles are generally used. Alternatively, data points obtained from contour crossing digitizing may be treated as any set of irregularly spaced points and the modelling function may be based on a three dimensional interpretation of the data.

Many numerical, statistical, and analytical modelling functions have been researched and developed for generating DEMs (Franke, 1979). The most often used functions in geographical applications are numerical in design. Numerical modelling functions work by assigning weights to data points nearest a location to be evaluated. A new elevation value is predicted based on the weights of these points. The inverse weighted distance method

of surfacing is the most common implementation of a numerical modelling function and can be found in virtually all commercial surfacing packages. A characteristic of numerical modelling functions is their sensitivity to anomalies and distribution patterns in the data. Most DEM surfaces generated using numerical modelling functions contain artifacts which are introduced by the functions and not by the data. The artifacts may be cleaned from the DEM using low-pass filters; however, the presence of artifacts signifies an underlying flaw inherent in numerical modelling functions. Numerical modelling functions are easy to comprehend and implement. These characteristics, combined with a low demand for computer resources, make numerical modelling functions attractive for surfacing applications even though flaws persist.

Statistical surfacing, also known as kriging, is similar to numerical surfacing with the exception that the weights assigned to initial data points are determined from semivariograms. The semivariogram gives a statistical measure of spatial continuity of regionalized data points (Davis, 1973). Points which are statistically significant are included in the modelling function while other points are not. Surfaces generated by kriging produce artifacts similar to the artifacts generated by numerical surfacing methods.

Analytical modelling functions work by fitting a continuous mathematical function through all initial data points. The mathematical surface is then evaluated at specific locations to predict new elevation values. Analytical surface modelling functions are not subject to the proximity induced artifact problems of numerical and kriging functions since the influence assigned to initial data points is not dependent on their locations relative to new values. All initial data points in an analytical modelling function contain equal significance in calculating new values. Although not utilized as frequently as the numerical and statistical modelling functions for geographic applications, analytical modelling functions provide the cleanest and most dependable surfaces for DEM production.

Chapter 3
Methodology Overview

Topographic data acquisition from secondary sources has traditionally been accomplished through manually digitizing contour maps. The process of digitizing requires significant investment in terms of operator training and capital expenditures involving specialized hardware and software. One of the objectives of this research was to develop a cost effective procedure for generating digital elevation models without the use of expensive and highly specialized hardware. An adaptation of digital image processing provided the methodology to fulfil this objective in a manner that was timely and accurate, yet required only the standard hardware and software used for image processing applications.

Test Data

The map sheet selected as a test case for techniques developed in this research was the 1:20,000 scale topographic map identified as 83C/01NW. The area was chosen for the variety of topographic features it contains (Figure 3.1). Within the 17 km by 14 km region covered by the map sheet there are steep mountain slopes, sharply defined ridges, deeply incised river valleys, shallow stream channels, low relief uplands, low relief flood plains, and several alluvial fans. The test area is also available from the Provincial Government of Alberta as a digital elevation model. The provincial DEM provided the basis for qualitative and quantitative comparisons between the results of this research and a commercially developed product.

Image Processing for Digital Data Capture

The premise behind using image processing techniques for digital data capture relies upon the highly precise spatial resolution of scanning devices, and on the generalized portrayal of elevations as contours on topographic maps. High precision in the spatial resolution of scanners enables assumptions to be made about relationships between the shapes and sizes of the pixels in a scanned raster image and the shapes and sizes of ground coverage the pixels represent. These assumptions allow for quick and

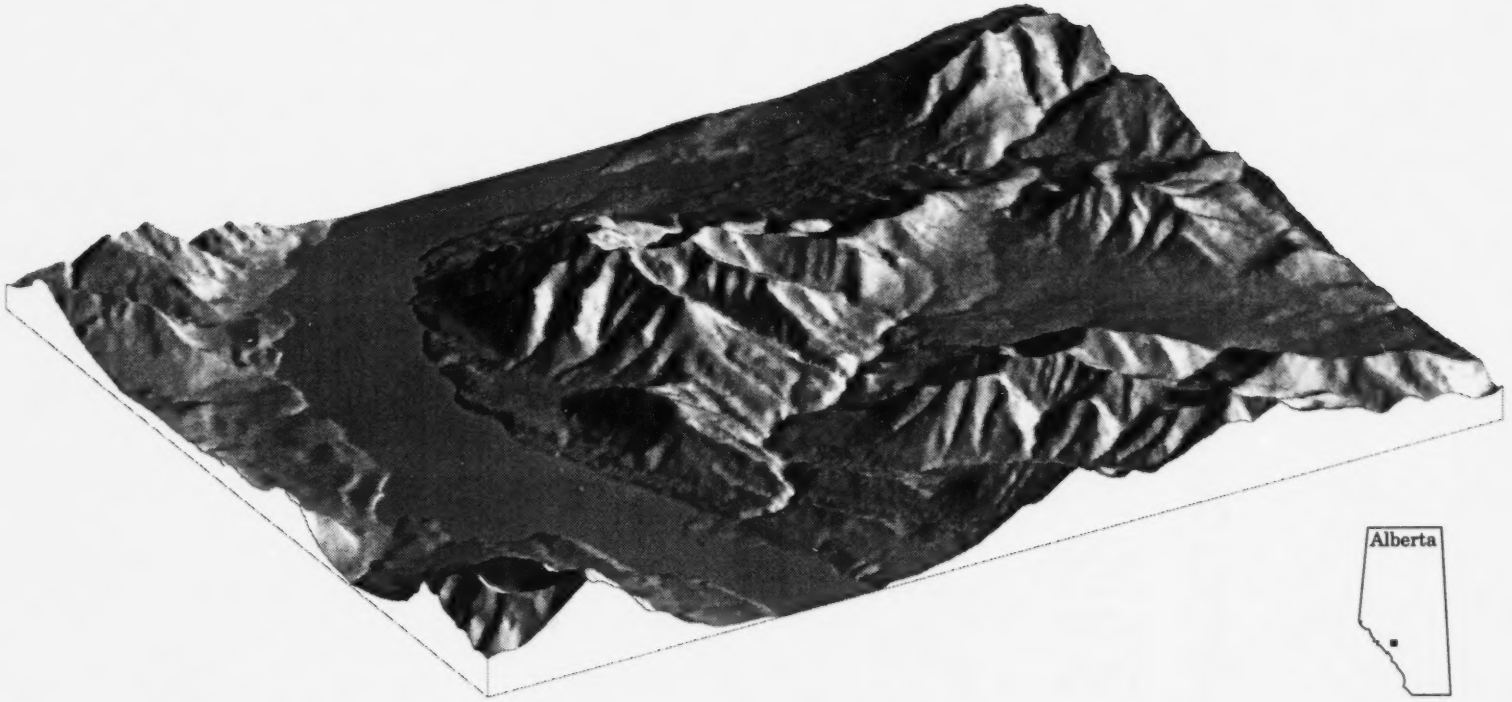


Figure 3.1. Three dimensional view of the topography in map sheet 83C/01NW. View azimuth is 210° at an elevation of 28°. Solar illumination is from an azimuth of 140° at an elevation of 30°. Vertical exaggeration is 1X.

accurate spatial location of features represented in an image limited only by the spatial resolution of the scan. Using image processing techniques, contour lines can be digitally encoded as grey tones or grey level values (GLVs). For an 8 bit grey scale image, there are 2^8 or 256 possible grey tones. A typical topographic map contains fewer than 100 unique contour levels which can easily be identified as GLVs in an 8 bit image.

Extraction of elevation information in the form of XYZ triplets from an encoded raster image is a straightforward exercise; knowing the world coordinates of a corner of a DEM grid and the size of an image pixel or grid cell are all that is necessary to calculate the two dimensional world coordinate values for every cell in the image. The elevation for a given point can be determined from the assigned grey tone using the encoding scheme to complete the XYZ triplet information. A simple program was written in C code to perform the extraction.

Accuracy concerns with applying image processing to digital data capture are related to the spatial location of captured elevation values. The spatial location of contours acquired using image processing is controlled by the spatial resolution of the scan used to capture the image. Current desktop scanners typically scan to a resolution of 0.00635 cm (158 dots per cm) which exceeds the accuracy contained in topographic maps where the pens used to plot contour lines may be 0.0127 cm or greater in thickness. The actual elevation values in a topographic map are generalized as contour lines. There is no interpolation of elevation during the data capture which ensures that elevation information is essentially at the same level of accuracy as that associated with the topographic map.

Data Management for Small Computers

Efficient management of data is important in all computer programming. When the amount of data is large and many items are manipulated repeatedly, efficient management is crucial to effective program design and execution. Research in computer science has produced many highly efficient methods for managing data in various computing environments (Aho et al., 1983; Claybrook, 1983). For situations where data are repeatedly searched and indexed, the most efficient techniques developed involve two distinct phases of implementation. The two phases are a pre-

processing phase designed to create an optimal data structure and a searching phase where the data structure is utilized. The definition of an optimal data structure depends heavily upon the nature of the data to be stored.

Spatially distributed elevation data captured for the purpose of generating DEMs can logically be visualized as records of elevation values stored at specific locations within a two dimensional plane. An efficient storage and retrieval algorithm for this data should take advantage of, or at least take into account, this multidimensional nature. Through the course of this research, multidimensional binary search trees were implemented as a highly efficient method for managing large amounts of data with a minimal amount of computer resources committed as overhead. The multidimensional tree algorithms were incorporated into several computer programs which were executed in both DOS and UNIX operating environments.

An Analytical Tiling Approach to Surfacing

Predicting unknown surface values from known sample coordinates is a complex task. Investigations into predicting surfaces has produced many techniques and methodologies with varied degrees of accuracy and success. The distinction is made between accuracy and success because the accuracy of a surface in representing topographic information is not always related to the successful use of the surface in an intended application. The targeted use of a generated surface can make a significant contribution in deciding how accurate the surface must be. Low order polynomial trend surfaces are a good example of low accuracy surfaces that are very successful at clearly presenting generalized information.

Multiquadric interpolation (Hardy, 1971) is a surfacing technique that has been proven highly accurate at predicting topographic surfaces (Franke, 1979; Hein, 1979: cited in Schiro and Williams, 1983; Schiro and Williams, 1984). Multiquadric interpolation is an exact-fitting analytical surfacing technique that provides neutral interpolation through areas of low sample point density while maintaining sharp control through areas of high density. Difficulties with implementing multiquadric interpolations occur with the large demand for computer resources required to develop a modelling function for a given set of data points. Using a "divide and conquer"

approach to reduce the surfacing area into adjacent surface tiles with associated sub-sets of data points removes the computer resource problems. If the surface and data points are reduced to small enough sub-sets then multiquadric interpolation techniques can be implemented even on small computer systems. The issue then becomes one of intelligently partitioning the data points into sub-sets in a manner that optimizes computational time while maintaining the characteristics of the surface being modelled.

The approach used to partition data points will have a significant impact on both the time needed to compute the surface and on the quality of the surface itself. An appropriate and efficient partitioning approach should make allowances for sudden and unpredictable variations in data point densities without artificially altering the topographic information contained within the patterns of point distributions. An adaptive surfacing approach that dynamically partitions data points and maintains the directional patterns within point distributions was developed. The adaptive tiling approach intelligently partitions data points before using multiquadric interpolation techniques to produce high quality surface segments which are combined to form a complete DEM. Adaptive tiling allows the surfacing routine to function adequately on any computer platform regardless of internal memory structure and memory limitations.

Chapter 4
Image Processing for Digital Data Capture

The image processing techniques required to capture elevation data from topographic maps are simple, generic, and are part of virtually all digital image processing systems. The hardware requirements are a flatbed scanner used to capture a grey scaled raster image of contour lines, and a computer with sufficient power and memory to process the image. Limitations in processing power and memory of the computer can be compensated for by segmenting the image into manageable sub-images during processing and recombining them to produce a final product. The image processing functions required are cropping, rotation, scaling, copying / pasting, thresholding, and painting. The image processing software utilized in this research was Adobe Photoshop version 3.0. Photoshop provides all the tools indicated above along with many others which, though useful, were not essential nor required in the completion of this work. Any image processing system which contains the basic operations stated above could have been used to achieve the same final results.

Scanning Topographic Maps

Conversion of elevation data from the paper map format to a digital file format occurred in five separate stages. Adobe Photoshop and associated image processing operations were central to the first four stages. The fifth stage involved converting the final processed raster image to XYZ point values and required a special program developed for that purpose.

The first stage was the actual capture or scanning of the topographic map. Scanning began with selection of a suitable spatial resolution which would cleanly differentiate most of the contour lines without providing excessive detail. Several small test scans were taken at various resolutions to identify a resolution which would capture contour lines at a width of 3 to 4 pixels (Figure 4.1). The reasons for selecting a resolution in this manner are twofold. First, the center of the contour lines can be identified by thresholding or clipping the grey level values. Placing elevation values at the center of the contour lines using a medium pixel resolution (Figure 4.1b) gives a higher level of accuracy than is possible with a coarse resolution

Figure 4.1. Sample scans at: a. coarse; b. medium; c. fine resolutions.

(Figure 4.1a). A very fine scan resolution (Figure 4.1c) would result in huge and unmanageable file sizes while incorrectly providing more location accuracy than the map actually contains. Second, the "magic wand" tool in Photoshop, a tool which can select contiguous areas of similar pixels, will only locate chains of pixels with contiguous edges as in Figure 4.1b and Figure 4.1c. Diagonal chains of single pixels (Figure 4.1a) can not be automatically selected with the wand tool. The wand tool is one of the previously mentioned useful, though not essential, functions which made encoding of the elevation data much more efficient.

Following determination of an appropriate resolution, the entire map sheet was scanned as 8 bit grey scaled image segments until complete coverage was achieved. Each of segment was geometrically corrected with the rotation operator until UTM registration marks were horizontally and vertically aligned (Figure 4.2). The segments were then combined to form a complete digital scan of the entire map sheet.

Image Processing

The second stage of data capture focused on cleaning and preparing the scanned image for data encoding. Cleaning the image involved using the digital eraser to remove pixels of text, symbols, and other markers which came in contact with the pixels of contour lines (Figure 4.3). If these "noise" pixels were not removed, the wand tool would include them as part of the contour lines when those specific contour lines were selected. Often several adjacent contours would be selected together when the "noise" bridged the spaces between them. A copy of the final cleaned image was then saved for use in the data reduction stage.

Elevation Encoding

The choice of which grey tones to assign to each contour level was determined by identifying the elevation extremes in the map through inspection. The range of elevations for map sheet 83C/01-NW proceeded from a low of 1316m at lake level to a high of 2820m with a contour interval of 20m. Therefore, there were (2820 - 1316) / 20 + 1 or 76 separate elevation levels to label. An elevation increase of 10m per grey tone would require a

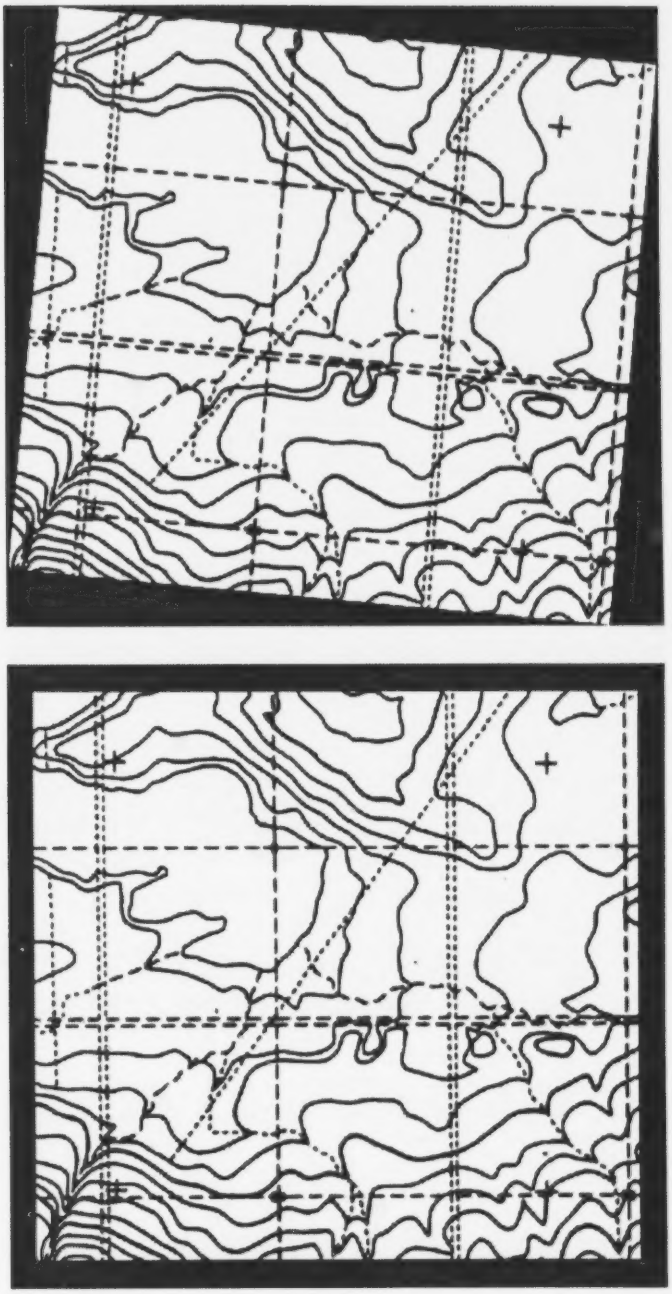


Figure 4.2. Rotation of scanned map segments for rectangular alignment of UTM registration marks.

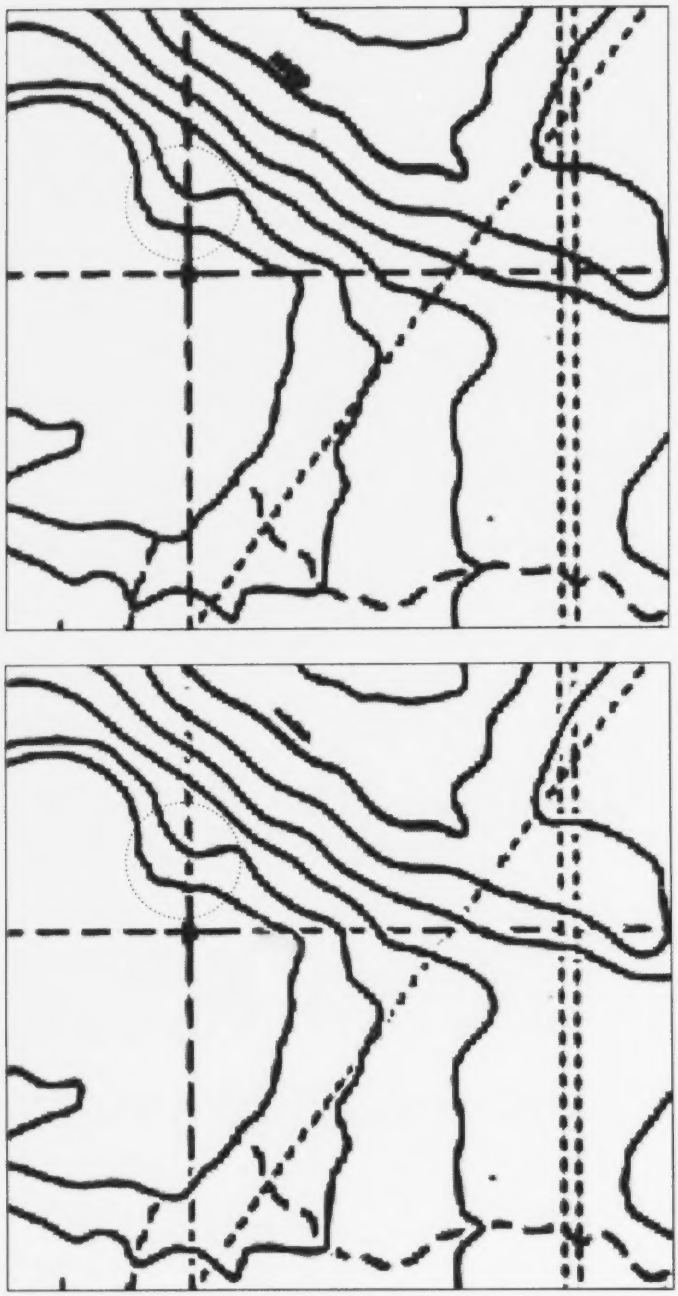


Figure 4.3. Contour lines are isolated by erasing connecting pixels along the contour borders.

sequence of 150 grey tones and would easily fit within the range of 256 tones available. An initial grey tone of 62 was chosen to represent elevation 1320m to enable easy visual differentiation between processed contours (dark grey to light grey) and unprocessed contours (black). Final selection of grey tones used to encode elevation data ranged from 62 to 212 and covered all contour elevations on the map.

Encoding elevation data was a simple repetitive cycle of manually selecting a contour then filling the selection with the appropriate grey tone value. The magic wand tool in Photoshop would select an entire contour line or continuous segment of a line permitting the entire set of pixels to be filled with a grey tone quickly and efficiently. The majority of contour lines in the test map were encoded using this select and fill cycle. Exceptions to the select and fill process occurred where steepness of the represented elevation changes caused the contour lines to merge. When contours merged the wand tool could not separate them for individual processing. The pencil tool was used to uniquely encode the separate pixels of merged contour lines.

Complete encoding of all contours in the test map was accomplished in several sittings and took approximately 28 hours including time spent cleaning the image in stage 2. For comparison purposes, a section of the map sheet was then encoded using traditional methods on a digitizing table. The time required to encode the entire map through digitizing was extrapolated from the sample and was determined to range between 35 and 40 hours depending on the care taken to digitize the center of contour lines. The time to encode the map using image processing techniques compares favorably with the traditional digitizing process. An additional benefit of the image processing approach is that locational accuracy is constant and consistent throughout the map and does not depend on the steady hand-eye coordination of the operator. Long periods of traditional map digitizing can lead to muscle fatigue and eye strain for the operator. Both of these physiological responses to protracted and repetitive digitizing motions can result in digitized points which do not coincide with the centers of contour lines.

Image Data Reduction

The fourth stage of encoding elevation data involved reducing the actual amount of encoded data while improving locational accuracy of the

retained information. The dual purpose procedure was achieved by thinning the encoded contour lines from their three to four pixel wide representations down to the single pixel centers of the lines (Figure 4.4). Thinning the lines was a two step process involving the image operators for thresholding, copying, and pasting. The first step was to threshold the cleaned grey scaled backup image saved in stage 2. Thresholding in Photoshop produces a black and white binary image where all grey tones less than the threshold are black and all others are white. The threshold level utilized was selected and adjusted visually in Photoshop until contour lines in the resulting binary image were one pixel wide. Care must be taken at this step to select a threshold that thins the contour lines without deleting segments of the contour centers. The real time preview option of Photoshop provides a useful tool for quickly adjusting and appraising the suitability of each threshold level.

The second step in data reduction required copying the white area of the thresholded binary image and pasting it into the encoded elevation image. Perfect registration between the two images allowed the white space of the binary image to mask off the sides of the contours in the encoded image in one quick and precise step. The final processed and encoded image was then written to disk as a raw binary image file.

Before the fifth and final stage of the data acquisition could proceed, some information had to be visually extracted from the encoded data file. Specifically, UTM coordinates of the relevant region of the image had to be determined. The UTM easting and northing dimensions of the image pixels were calculated from row and column values of the extreme UTM registration marks in the image. The equation used to calculate cell dimensions was:

UTM meters per cell = (UTM_Max - UTM_Min) / (Cell_Max - Cell_Min)

Knowing the pixel dimensions in UTM coordinates permitted proper determination of UTM values for the pixels in the corners of the image based on the internal location of the UTM registration marks. The information on the relationship between UTM values and pixel locations was utilized in stage five.

Figure 4.4. A contour mask is created by thresholding a copy of the scanned image. The mask is pasted over the final encoded image to thin the contours to their centers.

Extracting Elevation Information from a Raster Image

The fifth and final stage of capturing digital elevation data required extracting elevation locations from the implied location format of the raster to explicitly defined XYZ locations. A program was developed which automatically performed the necessary data conversions. The program prompts the operator for information defining the dimensions of a single cell in the raster, total size of the image raster, world coordinate values of the first cell in the raster, and the grey tone to elevation encoding used. The program was designed to ignore grey tone values of 0 and 255, which allows registration marks to be left in the image without compromising the encoding scheme. Once the required information is entered, the program proceeds to extract all encoded elevations as explicitly defined coordinate triplets. Depending on the resolution of the image scan, and on the degree of data reduction performed in stage four, the resulting file of elevation points may become very large and contain literally hundreds of thousands of values. In the case where the number of points becomes unmanageable for the computing resources available, a further reduction of data will be required before the actual surfacing program can be executed.

Chapter 5
Data Management for Small Computers

Surfacing DEMs using DOS based operating systems can be a challenging endeavor due to the potentially large number of data points involved, combined with the restrictive segmented memory architecture of the computer. A program designed to generate DEMs under these conditions must efficiently and effectively handle not only thousands of data values, but also the thousands of requests for data retrieval based on approximated spatial locations. Retrieval locations are described as approximated locations due to the fact that retrieval requests are in the form of "which N points are closest to location L". The spatial nature of digital elevation values, given in the form of XYZ triplet coordinates, suggest that a multi-dimensional handling of the data may be advantageous for purposes of rapid searching and retrieval. Several highly sophisticated and efficient techniques for handling multi-dimensional data have been developed in the field of computer science (Aho, 1983). The general classification under which these multi-dimensional algorithms are identified is "range searching" (Sedgewick, 1983).

Range Searching

The general premise of range searching as applied to geographic elevation data is that elevation values constitute records in a database indexed by two attributes representing the spatial location (Sedgewick, 1983, p. 335). Items are located through a search for all records which satisfy all attribute requirements as bounded by range conditions. For DEM surfacing, bounding range conditions are simply the X and Y limits identifying a rectangular area of interest. Elevation values which correspond to X and Y attributes located within the rectangular range are selected for processing. Many computer science texts explain in detail the merits of various range searching algorithms (Aho et al., 1983; Claybrook, 1983). For the purpose of this research, a multi-dimensional enhancement to the simple binary tree searching algorithm was employed.

Two Dimensional Binary Search Trees

Binary search trees are simple, efficient, dynamic searching methods based on one of the most fundamental algorithms in computing science (Sedgewick, 1983). Two-dimensional trees are dynamic, adaptable data structures which are very similar to binary trees but divide up a geometric space in a manner convenient for use in range searching (Sedgewick, 1983). Multi-dimensional binary trees are nearly identical to traditional binary trees with the difference being that at each level in the tree a different attribute is identified as the key to determine branching. In a simple two-dimensional search tree of geographic positional data the X and Y attributes function as branching keys on alternate levels (Figure 5.1).

A pre-processing algorithm is used to create the two-dimensional binary search tree from a data file before the actual range searching algorithm can be used. The code to construct a two-dimensional binary search tree is a straight forward modification of standard binary tree construction code which has been published in many computer science and algorithm texts (Tremblay and Bunt, 1979; Aho et al., 1983). The modification involves a switch to alternate the testing of X and Y coordinates on alternate levels of the tree. Published statistics for the efficiency of creating a binary search tree (Claybrook, 1983; Sedgewick, 1983) state that the average time to create a tree using randomly distributed points is proportional to NlogN, where N is the total number of points to be added to the tree. An important note is that randomly distributed points are used to determine the average construction efficiency. For specific combinations of data points the construction efficiency can hit a worst case scenario of an N^2 proportionality. Statistics for creating a two-dimensional binary search tree are the same as the statistics for creating the traditional binary tree, namely NlogN. Statistical similarity is consistent with the nearly identical algorithms required to create the two types of binary trees. As with the traditional binary search tree, a worst case scenario for creating a two-dimensional binary search tree can hit a proportionality of N^2.

Algorithms for traversing a binary search tree typically employ recursion to control branching and returning between levels of the tree. Recursive search routines are easy to design and are very easy to implement in most programming languages. The problem with recursion, however, is

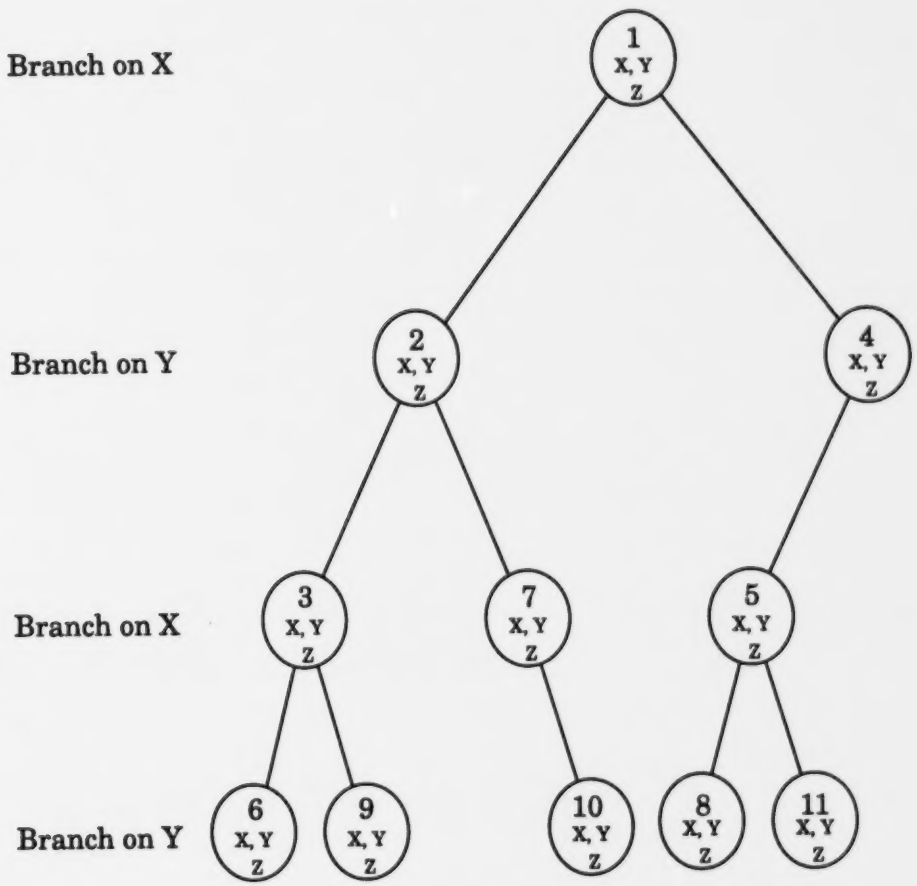


Figure 5.1. Sample two dimensional binary search tree with 11 nodes containing XYZ coordinate information.

that space in a computer's memory stack must be available to store system values every time a recursion call takes place. On a DOS based computer the stack space is at a premium and memory problems can rapidly develop when hundreds of recursion calls are made into a binary search tree containing tens of thousands of data values.

A non-recursive post-fix traversal algorithm for two-dimensional binary search trees was developed during the course of this research. The non-recursive search routine eliminated the stack problems on DOS based computers without impacting on the performance characteristics of the binary search tree algorithm. The branching logic of the non-recursive routine matched the branching logic in the traditional recursive search routine, however, an internal loop and two boolean flags were utilized to control traversal directions. Comparison of the non-recursive branching logic with the traditional recursion logic indicates that performance of the non-recursive routine matches performance of the recursive method. Published statistics for the efficiency of binary search tree traversals (Aho et al., 1983; Sedgewick, 1983) reveal that the number of checks needed to locate one point in a tree containing N points is proportional to logN. Therefore, the efficiency of searching for the R points contained in a defined range using a two-dimensional binary tree containing N points would be proportional to R+logN. These efficiency values indicate the average performance characteristics for binary search trees and would not be valid if points in the tree are distributed such that the worst case scenario developed. Random distribution of points helps to prevent the worst case scenario from developing.

Chapter 6
An Analytical Tiling Approach To Surfacing

Prediction, interpolation, and representation of topographic surfaces from initial sets of irregularly distributed location data has resulted in the development of many analytical and numerical surface-fitting methodologies. Franke (1979) and Hein (1979: cited in Schiro and Williams, 1983) investigated 29 and 8 different surfacing approaches respectively with the goals of evaluating the efficiency and accuracy of each method. A clear definition of what constitutes a surface is necessary to evaluate the characteristics of any surface generating process. Schiro and Williams (1983) proposed the following statement for defining a surface in terms of a model:

> Given the points (X_k, Y_k, Z_k), k=1,..,N over some domain (D(X,Y)), a function is desired which reproduces the given points and produces a reasonable estimate of the surface (Z) to all other points (X,Y) in the given domain.

Two key conditions of this definition provide limits which can be used to classify and evaluate the functionality of surfacing methodologies. The condition that a surfacing method "reproduces the given points" defines a boundary for classifying the method as either an approximation or an interpolation approach (Schumacher, 1976). Approximation approaches assume a degree of measurement error in the initial data making exact reproduction of the initial data undesirable. Least-squares based techniques are a common example of an approximation approach. Interpolation approaches assume that initial irregular data contain exact measurements of the topographic surface. Interpolation approaches preserve the exact measurements and can reproduce original sample data precisely.

The condition that a surfacing approach "produces a reasonable estimate of the surface" is a difficult condition to define or quantify since the intended application of a surface may strongly influence how reasonable the estimated results are. In both the Franke (1979) and Hein (1979) investigations, surfaces generated using a technique of multiquadric interpolating were judged the best in terms of surface accuracy and

computation time. Topographic surface generation using multiquadric interpolation is developed and evaluated in this work.

Multiquadric Equations

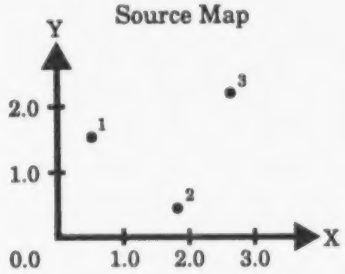
Multiquadric interpolation was developed by Dr. Rolland Hardy at Iowa State University (Hardy, 1971, 1972, 1975). Mathematically, a "quadric" is identified as a locus of points which satisfy a second degree polynomial equation. Spain (1960) defined a quadric surface as a locus of points whose coordinates satisfied any general equation of second degree. Multiquadric interpolation describes the process of evaluating multiple quadric surfaces defined in a common spatial domain to produce a solution common to each separate quadric surface. Mathematically a multiquadric-based method for surface generation can be written as:

$$Z = \sum_{i=1}^{n} C_i [Q(X,Y,X_i,Y_i)]$$

where each Q is a quadric surface (Schiro and Williams, 1984). The C_i's are obtained by evaluating the individual quadric surfaces (Q) resulting from substitutions of (X_i, Y_i, Z_i); i=1..N. The N resulting quadric equations are solved as a set of N simultaneous equations. Hardy (1971) provides an extensive analysis of the mathematical steps and principles involved with implementing multiquadric surface interpolations. Eyton (1974) provides a complete example solution for a simplified set consisting of three data points (Figure 6.1). The algorithms designed to implement multiquadric surfacing in this research solved the systems of simultaneous equations using a lower-upper (LU) triangular decomposition routine (Press et al., 1988). The LU decomposition technique was chosen for its characteristic of allowing new interpolation points to be evaluated through back substitution into the solved matrix (Johnston, 1982). A special note should be made that the LU decomposition method for solving simultaneous equations fails when the system is ill conditioned (Johnston, 1982; Press et al., 1988). When dealing with multiquadric equations, the system will become ill conditioned when

1. DATA:

Source Map



Sample Data

Obs.	Coord.	Z Value
1	X1 , Y1	Z1
2	X2 , Y2	Z2
3	X3 , Y3	Z3

2. MULTIQUADRIC HEIGHT SURFACE EQUATION:

General form: $Z = \sum_{j=1}^{n} C_j [(X_j - X)^2 + (Y_j - Y)^2]^{1/2}$

3. SOLUTION:

General form: $[C_j] = [a_{i,j}]^{-1} [Z_j]$

Expanding $[a_{i,j}]$ for sample data:

$$a_{11} = [(X_1 - X_1)^2 + (Y_1 - Y_1)^2]^{1/2}$$
$$a_{12} = [(X_1 - X_2)^2 + (Y_1 - Y_2)^2]^{1/2}$$
$$a_{13} = [(X_1 - X_3)^2 + (Y_1 - Y_3)^2]^{1/2}$$
$$\vdots \qquad\qquad \vdots$$
$$a_{33} = [(X_3 - X_3)^2 + (Y_3 - Y_3)^2]^{1/2}$$

Solution for sample data:

$$\begin{bmatrix} C_1 \\ C_2 \\ C_3 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix}^{-1} \begin{bmatrix} Z_1 \\ Z_2 \\ Z_3 \end{bmatrix}$$

4. MULTIQUADRIC HEIGHT SURFACE EQUATION FOR SAMPLE DATA:

$$Z = C_1 [(X_1 - X)^2 + (Y_1 - Y)^2]^{1/2} + C_2 [(X_2 - X)^2 + (Y_2 - Y)^2]^{1/2} + C_3 [(X_3 - X)^2 + (Y_3 - Y)^2]^{1/2}$$

Where: Z = Elevation at any location X,Y

Table 6.1. Example summary for evaluating a multiquadric solution.
Source: Eyton, 1974

two data points used in the solution of a system are located at the same (X,Y) spatial location. Care must be taken with multiquadric methods to ensure no points are duplicated in the initial data set.

Tiling

Approximation and interpolation methods for predicting surfaces may be classified as either global or local (Schiro and Williams, 1983) based on selection and relative weights assigned to points used in evaluating the surface. Local methods generate a modelling function utilizing just data points which provide the most influence nearest a location to be evaluated. Global methods employ all data values to determine a modelling function. Multiquadric equations are a global method for modelling topography as every data value entered into the equations may make a significant contribution to the final modelling function. A problem occurs when the number of data values becomes large. Each data value selected adds another simultaneous equation to the system. Solving a system of N simultaneous equations requires solving an N by N matrix of equation coefficients. Few computers are available (or accessible) which can solve the matrices that result when thousands or tens of thousands of data values are considered.

The computational problems raised by large numbers of data points can be resolved by treating the topographic surface being generated as a set of smaller overlapping surfaces defined by smaller, separate sets of data points. The small sets of data points can then be modelled by multiquadric equations to interpolate topographic subsets which are combined to form the complete DEM. The key to partitioning a set of data points into smaller subsets in an efficient and effective manner lies in the ability to adapt to unpredictable density changes in the distribution of the data. An early attempt at partitioning data points to support non-overlapping surface tiles was successfully developed by Eyton (1974): this methodology generated surfaces that did not contain artifacts where data density was uniform, but produced boundary effects around tiles where data density varied strongly.

Tile Boundary Effects

Experience through years of periodic investigations into surfacing research has shown that partitioning data point distributions into uniformly sized, contiguously spaced tiles or neighborhoods of points produced reasonable results for DEM surfaces where point distributions were dense. In areas where the point distribution was thin or sparse, partitioning points into uniformly sized tile units produced very undesirable results along the boundaries of each tile. In areas of thinly distributed points, seams appeared along the boundaries of each tile where the evaluated surfaces from adjoining tiles did not agree. The seams result from a lack of control when defining the edges of evaluated surface tiles due to the sparseness of data points in each partitioned region. The seams may be exaggerated or very subtle in the DEM surface but are recognizable by their perfect alignment along row and column directions.

Adaptive Tiling

Attempts to minimize effects of tile boundaries resulting from unpredictable variations in data point distributions resulted in an adaptive tiling scheme which takes advantage of the variations in data distribution to improve overall computational efficiency of the process. The basic tenet of adaptive tile partitioning is to subset data points dynamically based on local data distributions centered on the surface tile under evaluation at any given time. A surface tile is then interpolated only in the area which is well defined and controlled by the partitioned data values.

Tile boundaries are further reduced by selecting subsequent tile centers along the edges of previously evaluated tiles. The practice of selecting new tile centers along these edges guarantees up to 50% overlap between old and new tile surfaces. Tile overlaps are combined as a weighted blend based on a cell's distance to the new tile's center. Blending tile boundaries with the centers of subsequent tiles removed nearly all traces of tile boundaries in the resulting DEMs. Computational efficiency of the adaptive tiling method is improved relative to the uniform tiling method due to increased surface coverage generated from the solution of single sets of multiquadric equations in sparse locations. The sizes of systems of simultaneous multiquadric equations were coded to be the same for both

adaptive and uniform tiling methods, however, the variable tile size of the adaptive method permitted greater topographic surface interpolation in regions of low data point distributions and therefore less numbers of tiles needed to be evaluated.

Directional Point Selection

Adaptive tiling based on point density distributions reduces computational time and reduces the effects of tile boundaries within sparsely represented data regions; however, tile boundaries are still a problem along transition zones between densely and sparsely distributed regions. Tile boundaries which appear along these transitional zones result from disproportionate control across the area being interpolated due to sudden increases or decreases in the representation of data points (Figure 6.2). Investigations into ensuring balanced representation and control of data points throughout a particular partition produced a points partitioning based on directional modifications to the previously defined density modifications. In the directional representation scheme, points are selected for a partition based on proximity to the center of a tile and on location in one of eight sectors radially arranged around the tile center (Figure 6.3). Approximately equal numbers of points are selected from each sector giving uniform representation and control to all sides of a tile partition. The area interpolated by the multiquadric equations within the directional partition is determined by the shortest distance to the farthest point found in each of the sectors to ensure control of the tile surface, even at the edges. Tight control over the entire tile surface ensures smooth blending with adjacent overlapping tiles. Directional data point selection within an adaptive tiling scheme produced a multiquadric surfacing approach which was computationally efficient and generated DEM surfaces which were essentially boundary free, even when extremely high variations in point distribution densities were observed.

Post-Processing

Despite the reduction in tile boundaries produced on most data sets when using the adaptive tiling approach, specific arrangements of point distributions were found which would still generate small tile boundary

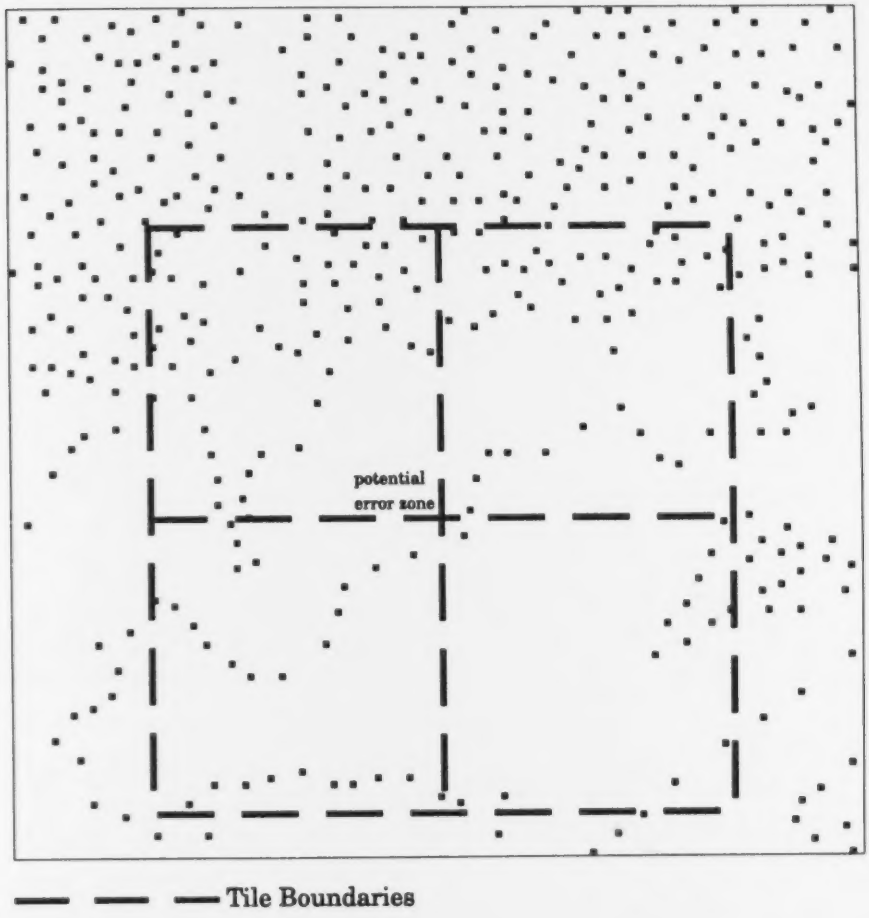


Figure 6.2. Point density variations over the area of a uniform tile may cause surface discontinuities with adjacent tiles.

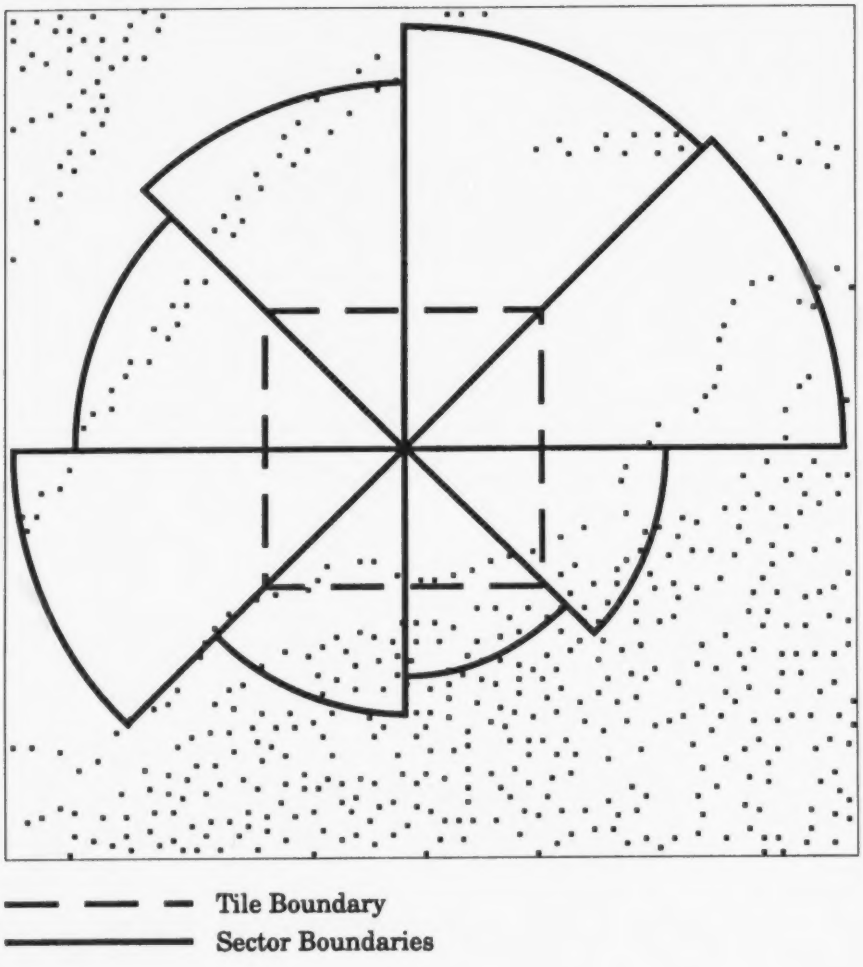


Figure 6.3. For adaptive directional tiling, similar numbers of points are selected from eight sectors radiating around the tile center. Sector sizes adapt to local density variations in data point distributions.

effects. The persistent tile boundaries were subtle and required highly thresholded derivative surfaces to detect. The tile boundaries were due to the spatial arrangement of specific data points causing the directional selection process to fail (Figure 6.4). When the directional selection process failed, a corner of the generated surface tile would not blend cleanly with adjacent tile surfaces of other evaluated point partitions. Investigations of these persistent boundary corners produced a hypothesis that corner boundary effects were a consequence of poor tile locations relative to the distribution pattern within the data points. In all boundary effects identified, moving the tile center from its computer selected location to the location of the boundary corner, fixed the break in the directional selection process and produced a DEM surface with no detectable boundary problems.

Testing the movement of tile centers while investigating boundary errors resulted in development of a post-processing program which is a companion program to the main DEM generating program. The post-processing program uses multiquadric equations to re-interpolate and blend an adaptive tile partition into a previously generated DEM. The new tile location is specified by the operator through an interactive interface. The test DEM generated in this research did not require use of the post-processing program; however, the unpredictable nature of point distributions made development of the post-processing program necessary.

Qsurf

The multiquadric equation methodology, efficient memory management, and adaptive tiling approach to surfacing as discussed previously were brought together in the form of a main program called Qsurf. Qsurf was the end product of many revisions of code, all aimed at maximizing computational efficiency while producing the cleanest and most reliable representations of surfaces from a variety of data sets. The program was developed on an Intel based 486/33 computer running the Microsoft DOS 6.2 operating system. The program was designed to work as efficiently as possible within the 640 kb memory restriction of the DOS operating system without resorting to DOS specific memory handlers. Qsurf was written in ANSI standard C using the Borland C++ version 4.0 compiler. Restricting code development to ANSI standard C permitted the program to be tested without modification on a wide range of computer platforms. Systems on

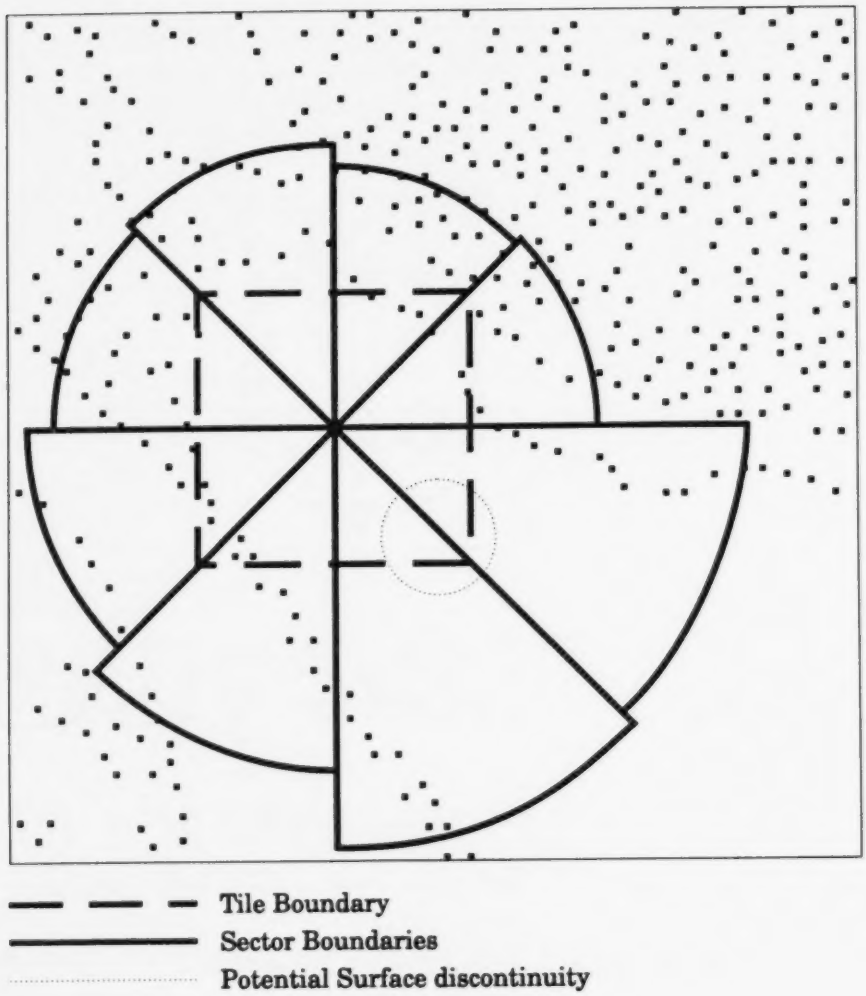


Figure 6.4. Even with adaptive directional tiling, specific patterns in data point distributions can cause surface discontinuities at tile boundaries.

which Qsurf was tested include an IBM RS/6000 running AIX, a Silicon Graphics Indigo running IRIX, a NeXT Station running the NeXT version of UNIX, an Intel based 486DX2/66, and an Intel based Pentium 90. In all tests, a numerically consistent surface was produced from common data test points attesting to the stability and reliability of the program with variations in operating environments.

Qsurf uses a non-recursive two-dimensional binary search tree data structure to optimize memory accesses with the potentially high volume of data points selected to define a surface. The generated surface is stored directly to disk where it is updated through random access routines. Storing the surface directly to disk eliminates memory problems which may result when very large surfaces are generated, while allowing maximum memory space for storing, selecting, and manipulating initial data points. The data points partitioned for evaluating a given tile are identified through a range search in the binary search tree. Identification of points in each of the eight sectors nearest the center of a tile is determined by a sorted list of distances. The program will allow initial data points to be entered as cartesian coordinate units or as spherical coordinate units. Permitting data values to be entered in both cartesian and spherical units ensures that surfaces generated by Qsurf are correct and suitable for both local and regional applications.

The number of points used in calculating a tile surface is controlled in Qsurf by a global constant definable by the operator at the start of program execution. The default value of 20 points per sector (160 per complete system of equations for one tile) was set to optimize program performance on the slowest DOS based computer used in testing. The number of points was set small enough to allow the entire two dimensional array of coefficients used in solving the simultaneous equations to be stored in a single 64 kb memory block. The same limiting value was maintained for tests on the high performance UNIX workstations to permit valid comparisons between all surfaces generated on DOS and UNIX computers while verifying the reliability and stability of the program. The impact that varying the number of points in a partition has on the performance of Qsurf is presented in Figure 6.5. The number of points selected for inclusion in a set of simultaneous equations determines the DEM surface area evaluated in the resulting tile. As the number of points increases the size of the tile increases producing a lower total number of tiles and sets of equations which must be solved. The

Surfacing Time vs Sector Points

Compiled on an Intel 486/33 computer
Note: Test File contained 7434 points

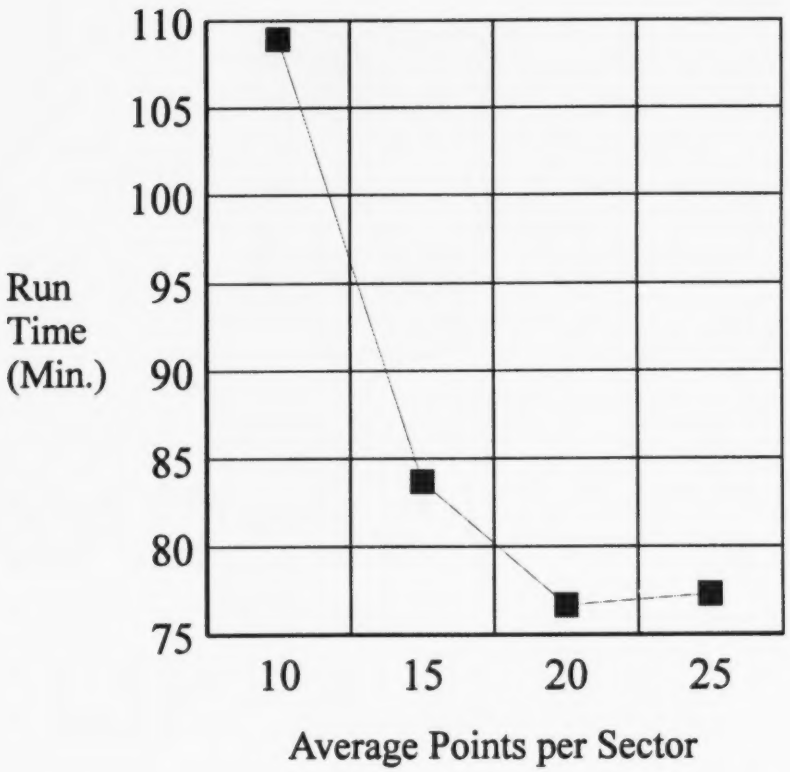


Figure 6.5. Performance chart indicating the relationship between total surfacing time and average number of points selected from each sector of a tile partition.

lower number of sets of simultaneous equations is reflected in Figure 6.5 where the execution time decreases as the number of points increases. When the number of points increases to the value where the size of a set of simultaneous equations exceeds a 64 kb memory block, execution time begins to increase as the time savings obtained by processing a lower number of equations sets is more than offset by the increase in time spent on memory swapping.

Chapter 7
Comparisons with the Alberta 1:20,000 DEM

The DEM surface representing the test area as produced by Qsurf was checked for validity and reliability through comparisons with a DEM supplied by the Provincial Government of Alberta. The Government of Alberta DEM was produced at a scale of 1:20,000 using a commercial program called SCOP. The data supplied to the SCOP program was obtained from direct measurements of stereo ortho-photo images. Numerical and visual comparisons between the two DEM products provided a rigorous, though potentially unfair, evaluation of the Qsurf methodology. The unfair nature of the comparisons is a consequence of using primary source data for the SCOP DEM and secondary source data for the Qsurf DEM. The primary source data used for the SCOP DEM provided a much higher level of terrain specific information than was available from the secondary source. Comparisons between the products was considered valid despite the different data sources because the SCOP product presented a quality controlled base-line surface upon which to evaluate the unknown product generated by Qsurf. The comparisons demonstrated that multiquadric interpolation, combined with an adaptive tiling approach, produced a DEM that was a valid and reliable representation of an actual terrain surface. In nearly all cases, differences between the SCOP DEM and the Qsurf DEM could be explained by the different levels of high frequency detail contained within the primary and secondary data. The programs which generated the derivative surfaces used in the comparisons were developed specifically for DEM analysis by Eyton (1991, 1995) and are released under the collective package name of TERRA FIRMA. In the comparisons presented, derivative surfaces generated from the SCOP DEM are displayed at the top of the figures and the corresponding surfaces generated from the Qsurf DEM are presented at the bottom.

Edge Contours

Edge contour images of the DEMs (Figure 7.1) were generated using a base reference elevation of 1300 meters and a contour interval of 50 meters. The major difference between these two images results from the smoother

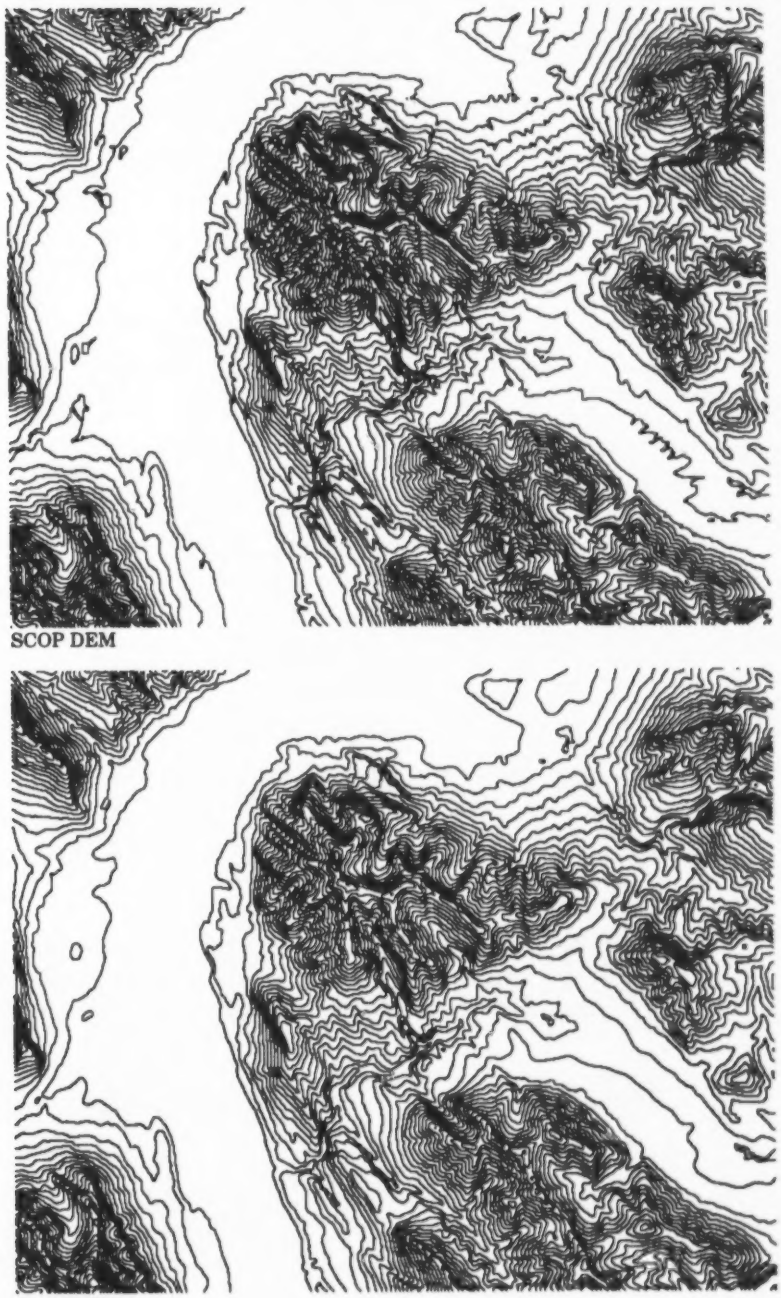


Figure 7.1. Edge contour images. Base reference elevation is 1300m. Contour interval is 50m.

nature of the Qsurf DEM. Contours extracted from the Qsurf DEM are more fluid than the angular contours of the SCOP DEM. Sharper angularity in the SCOP DEM surface resulted from the application of high frequency surficial information in the primary source data. The high frequency data provided information for defining breaklines, divides, and surficial modulations when the surface was generated.

Lambertian Light Model

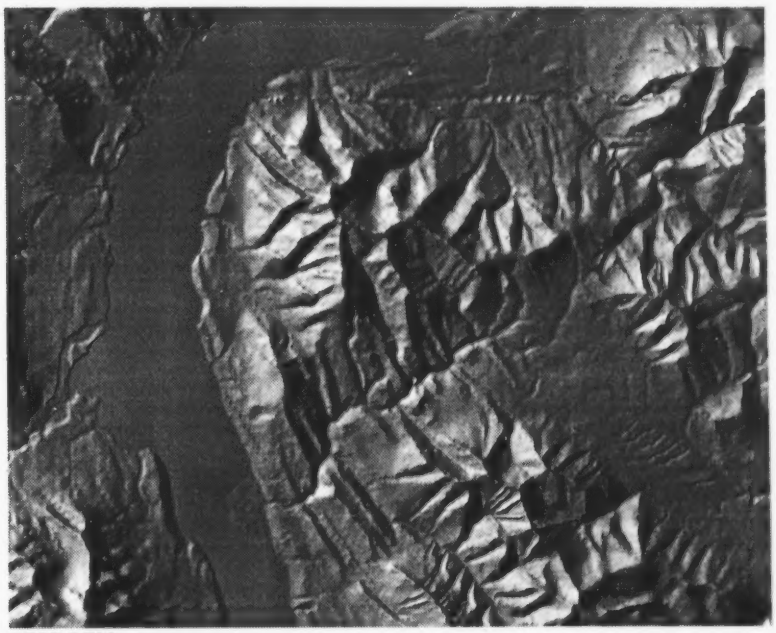
Lambertian lighting models of the two DEMs show both the similarities and differences between the surfaces (Figure 7.2). The SCOP DEM appears sharper and more defined due to small surficial features like the shallow drainage channels in the lower right area of the image. Details such as the shallow channels were not available in the secondary data and are not present in the Qsurf DEM. Structurally the two surfaces appear identical. The artificial sun used to illuminate the surfaces was placed at an azimuth of 300 degrees and at an altitude of 30 degrees. The light models were clipped at 5% on each tail of the Lambertian light values distribution to enhance the internal detail of the resulting images.

Slope Magnitude

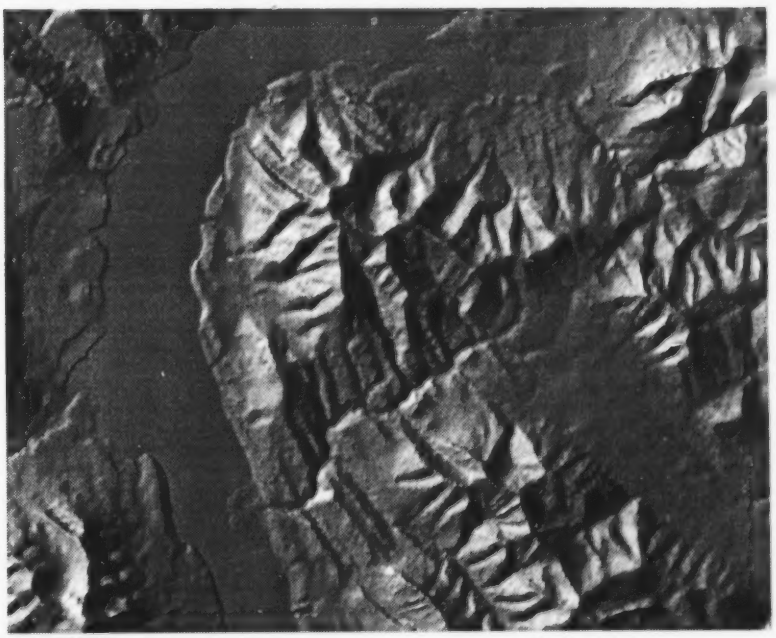
Gray scale images of the slope distributions for the DEMs were almost identical in appearance (Figure 7.3). Small areas of discernable differences between the two images were a product of small deviations in the slopes along shallow drainage channels located in the SCOP DEM. Shallow channels were not present in the initial Qsurf data which accounts for the absence of the corresponding slope changes in the Qsurf DEM. Transitions of slope magnitude are not as sharply defined in the Qsurf DEM image as they are in the SCOP image due to differences in DEM sharpness and definition as previously explained.

Across Slope Curvature

Images of across slope curvature derivatives (Figure 7.4) present the first significant differences between the SCOP and Qsurf DEMs. Across slope

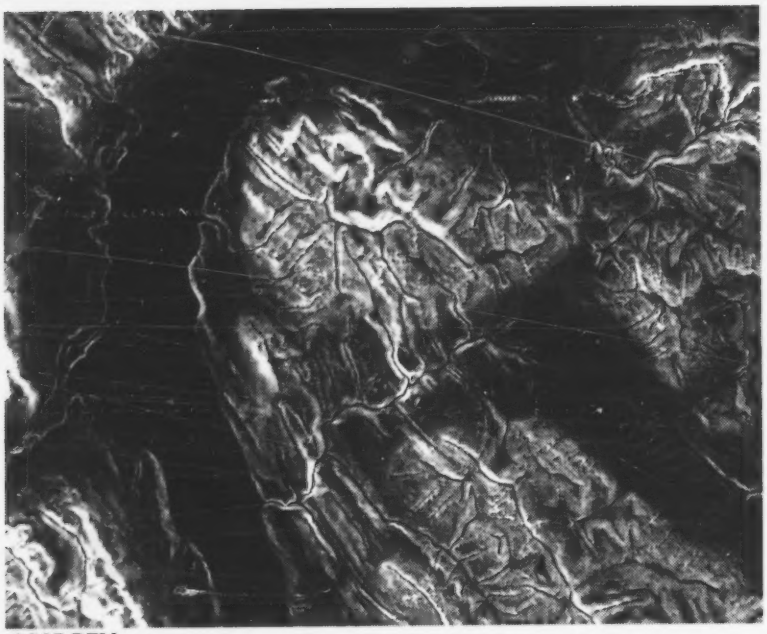


SCOP DEM

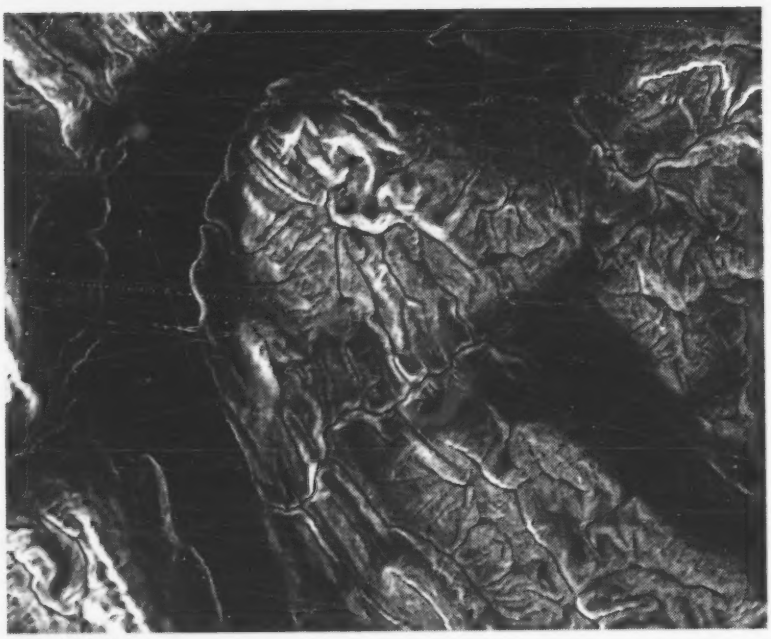


Qsurf DEM

Figure 7.2. Relative radiance images using a Lambertian Light model. Solar illumination is from 300° at an elevation of 30°.

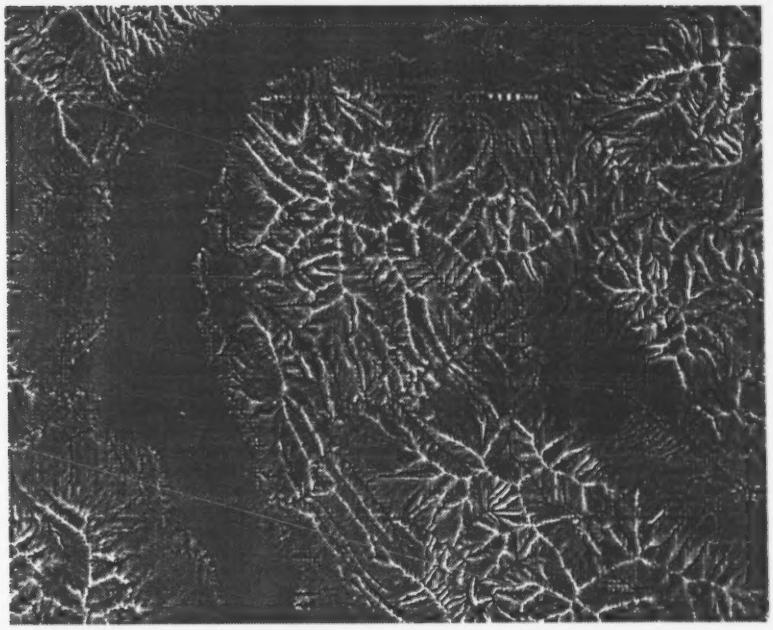


SCOP DEM

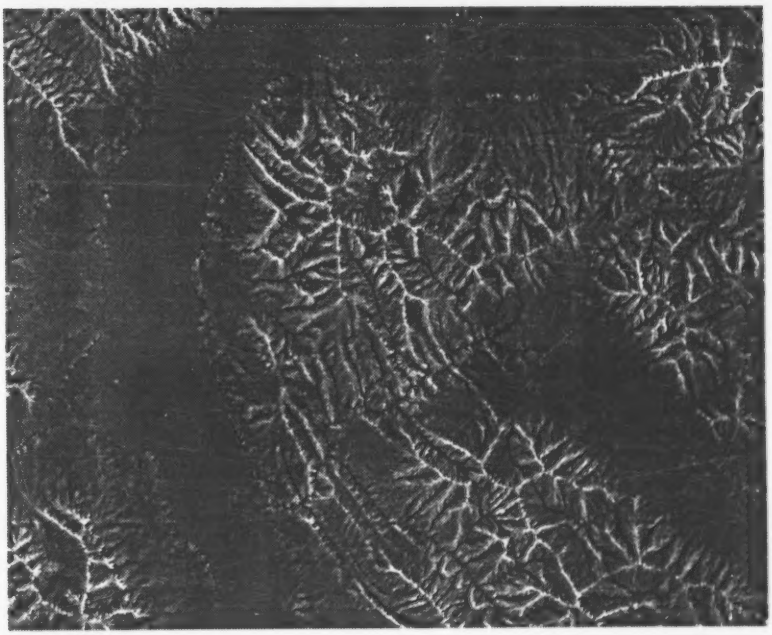


Qsurf DEM

Figure 7.3. Slope magnitude images. Maximum magnitudes were clipped at 48° of slope to enhance low-magnitude slope details.



SCOP DEM



Qsurf DEM

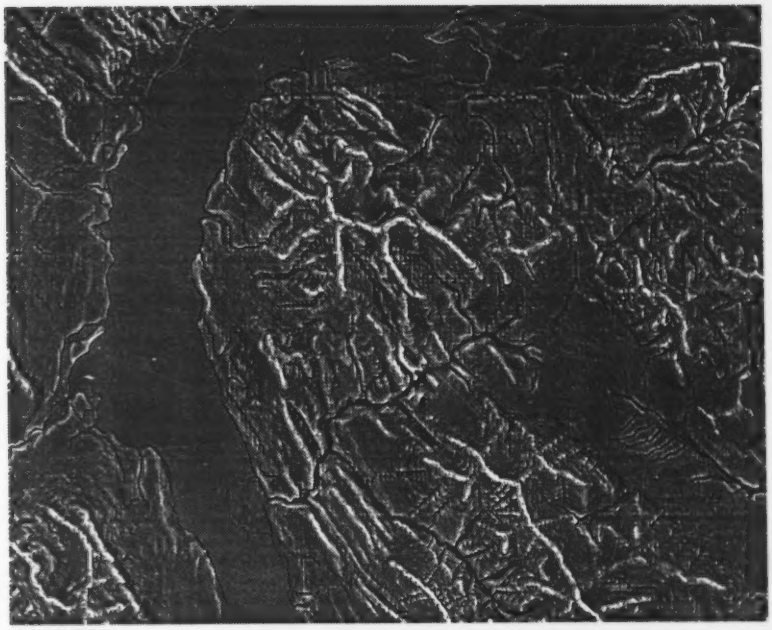
Figure 7.4. Across slope curvature scaled between -80° and 80° of change in slope per 100m.

curvature derivatives reveal the concave and convex curvatures across a slope face at each location in the DEM. Curvature units in these images are defined as degrees of curvature per 100 meters. The images were produced by scaling the curvatures between -80.0 and 80.0 which represented a 3% clipping of the most extreme concave and convex curvatures. The images show that curvatures along the channels and divides are very similar between the two DEMs. The Qsurf DEM across slope curvature image presents smooth transitions of curvature between divides and channels with little or no change in across slope curvature through level and flat areas. The across slope curvature image of the SCOP DEM also presents smooth transitions between the divides and channels. However, the SCOP DEM image also reveals artifacts in the DEM resulting from the initial data sampling and the interpolation method evaluated in generating the DEM.

Across slope curvature through flat and level areas of the SCOP DEM show the location of sample points use to interpolate the DEM as well as uniformly spaced curvature discontinuities resulting from linear interpolation of cell values along row and column directions. When linear interpolation is utilized for interpolating unknown elevation values, the curvature over the interpolated range drops to zero. Discontinuities caused by sudden drops in curvature are evident in the second derivative products such as across slope or down slope curvature. Discontinuities caused by linear interpolation are not desirable and can drastically interfere with curvature calculations or estimations subsequently extracted from the DEMs. Curvature discontinuities did not occur in the Qsurf DEM due to the smooth, neutral, and non-linear interpolations that result from utilizing a multiquadric equation approach.

Down Slope Curvature

Down slope curvature derivatives present information similar to that presented by across slope curvature derivatives. Down slope curvature derivatives describe curvature down the face of a slope as the rate of change of slope per 100 meters. The SCOP and Qsurf down slope curvature images (Figure 7.5) were produced by scaling the derivatives between values -80.0 and 80.0. The images show smooth transitions between convex down slope curvature at the tops of divides and concave down slope curvature at the



SCOP DEM

Qsurf DEM

Figure 7.5. Down slope curvature scaled between -80° and 80° of change in slope per 100m.

bottom of drainage channels. As in the across slope curvature comparison, the Qsurf DEM contained smooth curvature continuity across flat and level areas where the SCOP DEM contained discontinuities resulting from linear interpolations of elevation. Sharp definitions of the artifacts resulting from curvature discontinuities in the SCOP DEM image are strong enough to visually interfere with the valid curvature information being presented.

Statistical and Numerical Comparisons

Numerical comparisons between the SCOP and Qsurf DEMs provided some favorable and surprising results. A regression analysis in which the Qsurf DEM was regressed onto the SCOP DEM produced a coefficient of correlation of 0.9999. The coefficient of correlation was higher than anticipated in light of the differences in surface detail between the DEMs. The high correlation coefficient, combined with the visual information presented, gives strong support to the validity of the developed surfacing methodology of generating DEM surfaces from secondary data sources. The comparison results support use of Qsurf generated DEMs as high quality and reliable substitutes to DEMs generated from primary data sources when such DEMs are not available or affordable.

A residual difference surface was created to evaluate how closely the interpolated QSURF elevations approximated the corresponding SCOP values. The residual surface was produced by subtracting the Qsurf DEM from the SCOP DEM. Resulting difference values were presented in an image form (Figure 7.6) by scaling the differences within a range of 10 meters on either side of an exact approximation. The selected range of 10 meters represented one half the contour interval obtained from the topographic map. An important characteristic of the residual difference image supports the distinctions between the DEMs as a consequence of the two types of data sources used. Results of the residual difference image indicate that in all cases drainage channels were shallower in the Qsurf DEM than in the SCOP DEM, while tops of drainage divides were lower in the Qsurf DEM than in the SCOP DEM. The displacement of the channels and divides is evident in the image where all divides appear in light tones, while all channels appear in dark tones. The characteristic displacement of channel bottoms and ridge tops are a result of the SCOP program having access to information defining

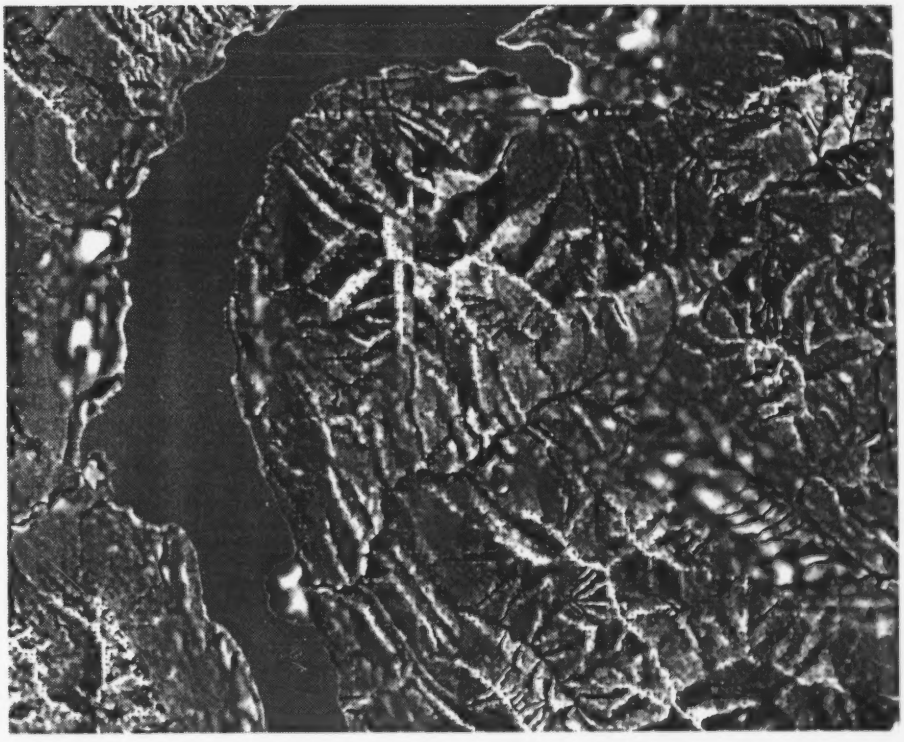


Figure 7.6. Residual difference image produced by subtracting the Qsurf DEM from the SCOP DEM. Differences are scaled between -10m (black) and +10m (white).

exact locations of these features, while the Qsurf program had to interpolate the location of these features based on the nearest contour levels. Neutral interpolation of these features when using the multiquadric equation method produced channel bottoms at slightly higher elevations than in the SCOP DEM and ridge tops at slightly lower elevations. A cumulative breakdown of the residual differences between the SCOP and Qsurf DEMs is presented in Table 7.1. Numerical evaluations of residual differences between the DEMs indicated that 94.4% of the elevations generated by Qsurf were within one half a contour interval of their corresponding elevations in the SCOP DEM. The one half contour interval break point meant that 94.4% of the Qsurf generated elevations were within 10 meters of the base-line elevations. A stricter evaluation of the differences concluded that 78.15% of the Qsurf generated elevations were within 5 meters or one quarter contour interval of the base-line elevations.

Table 7.1. Residual Surface Cumulative Frequency Distribution.

CLASS	LOWER CLASS LIMIT	UPPER CLASS LIMIT	FREQUENCY	PERCENT FREQUENCY	ACCUMULATED PERCENT FREQUENCY
1	-10.5000	-10.0000	9237	2.488	2.488
2	-10.0000	-9.5000	1431	.385	2.874
3	-9.5000	-9.0000	1609	.433	3.307
4	-9.0000	-8.5000	1853	.499	3.806
5	-8.5000	-8.0000	2110	.568	4.374
6	-8.0000	-7.5000	2435	.656	5.030
7	-7.5000	-7.0000	2768	.746	5.776
8	-7.0000	-6.5000	3158	.851	6.627
9	-6.5000	-6.0000	3593	.968	7.594
10	-6.0000	-5.5000	4194	1.130	8.724
11	-5.5000	-5.0000	4638	1.249	9.973
12	-5.0000	-4.5000	5362	1.444	11.418
13	-4.5000	-4.0000	6101	1.643	13.061
14	-4.0000	-3.5000	7038	1.896	14.957
15	-3.5000	-3.0000	8060	2.171	17.128
16	-3.0000	-2.5000	9456	2.547	19.675
17	-2.5000	-2.0000	11044	2.975	22.650
18	-2.0000	-1.5000	12413	3.344	25.993
19	-1.5000	-1.0000	14498	3.905	29.898
20	-1.0000	-.5000	16311	4.394	34.292
21	-.5000	.0000	18632	5.019	39.311
22	.0000	.5000	73138	19.700	59.011
23	.5000	1.0000	19861	5.350	64.361
24	1.0000	1.5000	17327	4.667	69.028
25	1.5000	2.0000	15104	4.068	73.097
26	2.0000	2.5000	13216	3.560	76.656
27	2.5000	3.0000	11014	2.967	79.623
28	3.0000	3.5000	9697	2.612	82.235
29	3.5000	4.0000	8304	2.237	84.472
30	4.0000	4.5000	7202	1.940	86.412
31	4.5000	5.0000	6384	1.720	88.131
32	5.0000	5.5000	5631	1.517	89.648
33	5.5000	6.0000	4845	1.305	90.953
34	6.0000	6.5000	4186	1.128	92.081
35	6.5000	7.0000	3838	1.034	93.115
36	7.0000	7.5000	3240	.873	93.987
37	7.5000	8.0000	2753	.742	94.729
38	8.0000	8.5000	2404	.648	95.376
39	8.5000	9.0000	2225	.599	95.976
40	9.0000	9.5000	1869	.503	96.479
41	9.5000	10.0000	1582	.426	96.905
42	10.0000	10.5000	11489	3.095	100.000

Chapter 8
Summary

Digital elevation models have become a familiar and often vital database for studying, planning, and mapping landforms. Our need to better understand the world fuels a demand to provide quality DEM products for an ever widening base of applications. Generating DEMs necessary for many of these applications can be an expensive and time consuming procedure. A method for converting contour information from topographic maps into high quality DEMs both accurately and efficiently was investigated and developed. Explorations of an analytical tiling approach to surfacing resulted in a DEM generating tool adaptable to nearly any computer system and capable of processing nearly any size elevation data set. The DEMs generated by this program were shown to be comparable in quality to DEMs generated directly from ortho-photo models.

Image processing tools for computer systems have evolved significantly both in quality and affordability in recent years. Rudimentary image processing tools are even available as shareware or freeware on many computer bulletin boards. Adapting the tools and techniques of image processing to fulfil the traditional role of contour digitizing provides a means for even the most inexperienced of users to acquire digital topographic information in an accurate and affordable manner. Although specialized tools are available which can convert scanned maps to digital products using hybrid scanners and pattern recognition software, the use of generic scanners and image processing tools to acquire topographic information is thought to be both a novel and a timely approach.

Analytical methodologies for surface generation have been reviewed and reported for decades (Hardy, 1971; Eyton, 1974; Franke, 1979; Schiro and Williams, 1984). Although capable of generating DEM surfaces superior to surfaces produced using numerical methods (Eyton, 1974; Franke, 1979; Hein, 1979; Schiro and Williams, 1984), analytical surfacing methodologies are rarely used in geographical applications. The intense allocation of computational resources necessary to effectively utilize analytical methods may be a contributing factor to their lack of popularity. Techniques for efficiently implementing multiquadric interpolation methodologies in a tool for generating DEM surfaces have been proposed. The developed analytical

tiling approach to surfacing resulted in a DEM generator that produces exact fitting surfaces which are nearly free of all artifacts. The implementation of two dimensional binary search trees for data storage, and the development of directionally adaptive data partitioning with dynamic sensitivity to data densities were key factors in the successful completion of the goals set out for this research. Strict adherence to hardware generic coding ensured the portability of the tools developed through this work.

Comparisons between the DEMs produced through this research and DEMs produced from ortho-photo models may appear unfair given the superior quality of data available from ortho-photos, however, such comparisons are necessary to fully evaluate and appreciate the quality of DEMs which can be obtained from simple contour maps. Although lacking in some high-frequency surficial details, the test DEM produced through this work generated derivative surface products which reproduced characteristics of the actual terrain. Comparisons of second derivative images extracted from the two DEMs demonstrated the improved curvature results produced through analytical interpolations as compared to numerical interpolations.

Techniques and methodologies for performing a task or accomplishing a goal are always the potential victims of future enhancements and innovations. The methodologies and tools developed in this research are no exceptions. Eventually, new or improved methods of dealing with cartographic and topographic information will obviate the need for manually producing DEMs. For the present, however, the innovative techniques and tools presented in this paper provide an alternative means for producing high quality digital elevation models.

References

Aho, A.V., J.E. Hopcroft and J.D. Ullman: 1983, Data Structures and Algorithms, Addison-Wesley Publishing Co. Inc.

Claybrook, B.G.: 1983, File Management Techniques, John Wiley & Sons Publishing, Inc.

Davis, J.C.: 1973, Statistics and Data Analysis in Geology, Second Ed., John Wiley & Sons Publishing, Inc.

Eyton, J.R.: 1974, An Analytical Surfacing Methodology for Application to the Geometric Measurement and Analysis of Landforms, Unpublished Ph.D. dissertation, University of Illinois at Urbana-Champaign.

Eyton, J.R.: 1987, Morphometrics of the Chasquis Invitational Rocky Mountain Road Race, Sport Place, Technical Notebook: 39-47.

Eyton, J.R.: 1991, Rate-of-Change Maps, Cartography and Geographic Information Systems 18(2): 87-103.

Eyton, J.R.: 1995, TERRA FIRMA: A display and analysis package for raster data, Unpublished software, Department of Geography, University of Alberta, Edmonton.

Franke, R.: 1979, A Critical Comparison of Some Methods for Interpolation of Scattered Data, Report # NPS-53-79-002, Naval Postgraduate School, Monterey, Calif.

Hardy, R.L.: 1971, Multiquadric Equations of Topography and Other Irregular Surfaces, Journal of Geophysical Research 76(8): 1905-1915.

Hardy, R.L.: 1972, The Analytic Geometry of Topographic Surfaces, Proceedings, American Congress on Surveying and Mapping 32: 163-181.

Hardy, R.L.: 1975, Research Results in the Application of Multiquadric Equations to Surveying and Mapping Problems, Surveying and Mapping 35(4): 321-332.

Hein, G. and K. Lenze: 1979, Zur genauigkeit und prodiktionsmethoden, Zeitschrift fuer Vermessungswesen 104: 492-505.

Johnston, R.L.: 1982, Numerical Methods, A Software Approach, John Wiley & Sons Publishing, Inc.

Kumler, M.P.: 1994, An Intensive Comparison of Triangulated Irregular Networks (TINs) and Digital Elevation Models (DEMs), Cartographica 31(2), Monograph 45.

Press, W.H., B.P. Flannery, S.A. Teukolsky and W.T. Vetterling: 1988, Numerical Recipes in C, The Art of Scientific Computing, Cambridge University Press.

Schiro, R. and G. Williams: 1983, An Adaptive Method for Numerically Modeling Large Numbers of Irregularly Spaced Data, Auto-Carto Six 2: 252-261.

Schiro, R. and G. Williams: 1984, An Adaptive Application of Multiquadric Interpolants for Numerically Modeling Large Numbers of Irregularly Spaced Hydrographic Data, Surveying and Mapping 44(4): 365-381.

Schumaker, L.L.: 1976, Fitting Surfaces to Scattered Data, Approximation Theory II, Academic Press, New York.

Sedgewick, R.: 1983, Algorithms, Addison-Wesley Publishing Co. Inc.

Spain, G.: 1960, Analytical Quadrics, International Series of Monographs in Pure and Applied Mathematics 14, Pergamon Press, New York.

Stephanovic, P.: 1988, Digital Elevation Models, Data Presentation, ITC Class Manual.

Tremblay, J. and R.B. Bunt: 1979, An Introduction to Computer Science: An Algorithmic Approach, McGraw-Hill Book Co. Inc.